A new statistical method to assess potential debris flow erosion

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Abstract. Debris-flow erosion patterns were investigated for two adjacent catchments, Molinara and Val del Lago creeks (Eastern Alps, Trento Province, Italy), where two debris flows were triggered by an intense storm in the summer of 2010. Both basins have been inactive over the last two centuries. The debris flows were activated by channel and bank erosion under stable bed conditions before the event. The erosive process was analysed by combining a field campaign (two hundred cross sections were surveyed along the creeks) and pre- and post-event LiDAR surveys. Data were analysed by selecting morphologically-homogenous channel reaches and deriving for each reach: erosion depth, creek width, eroded volume and peak discharge. Investigating the frequency distribution of the erosion depth we found out that it follows an EV1 probability distribution. On this basis, a new approach has been proposed to predict event volumes when the expected maximum potential depth erosion is known. The procedure would be of high interest in predicting debris flow volume in mountain channels characterized by long silent periods.

1 Introduction

Villages and infrastructure in Alpine regions are exposed to rapid mass movements, including debris flows. Several studies aimed to understand these processes, but fundamental questions concerning hazard assessment, mass growth along the flow path, and the variability of the processes remain open [1–3]. Adopting a qualitative approach, the first studies on erosion showed a high variability of the process and a strong influence of the local channel slope.
The methods generally used to quantify the expected debris-flow volume initially focused on the field estimation of entrainable sediment. Such criteria are based on a geomorphic reach-by-reach estimation of sediment availability along the stream network [4,5]. More recently, the quantification of debris flow erosion is increasingly supported by high-resolution topography surveys and digital surface analysis [6,7] combined into the geomorphic estimation procedures.
A database collected by [8] shows a statistical fingerprint of erosion depth. Other studies proposed empirical equations able to predict the depth of erosion based on channel and basin geomorphic variables such as channel slope [9–11]. In contrast, [12,13] did not find a major slope influence on erosion. Combining field survey data with high-resolution digital terrain models DTM, [2] emphasized the flow front height to be the key variable in erosion processes. Laboratory experiments and numerical models have took into consideration bulking and de-bulking processes along with sediment concentration, yield and shear stresses [14–16]. However, studies that require the back-calculation of complex field conditions suffer from difficulties in describing the channel bed geology, the boundary conditions and the basin/channel morphometry /morphology [8].
The two debris flows that occurred in the Molinara and Val del Lago catchments, investigated in this study, enlarge the knowledge of in-channel erosion processes through the analysis of data and conditions scarcely investigated in the literature. The research objective is to test the hypothesis that at the scale of a formative/highly erosive debris-flow a statistical fingerprint of the erosion depth exists and it can be used as a tool to predict the expected debris-flow volume.

2 Study area and the 2010 event

The study area is composed of two adjacent catchments located in Eastern Trentino (Alps, Northern Italy, 11.288091°, 46.140849°) on the NW oriented side of the Costalta peak (1955 m a.s.l., Fig. 1). Both basins are mainly covered by forest (Norway spruce and larch). Their channels are incised on a thin alluvial Quaternary cover over a massive porphyritic platform (Ring and Richter, 1994). The drainage network is well developed and rainstorms normally produce flood events without significant bed load transport. Effectively, there is no documentation noting the occurrence of significant debris flows in the 200 years preceding the severe event that occurred in summer of 2010.
The catchment area of the Molinara torrent is 0.88 km^2, extending from 1113 to 1955 m a.s.l. The mean slope of the catchment and main channel is high, equal to 70% and 37%, respectively. The total stream network is 4 km

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long, 1.7 km of which constitutes the main stream. The Molinara torrent network flows in a deeply incised valley and is characterised by low sinuosity. The catchment of Val del Lago torrent has an extension of 0.42 km^2 and the elevation ranges from 1024 to 1722 m a.s.l. The mean slope of the main channel (1.5 km long) is 28%.

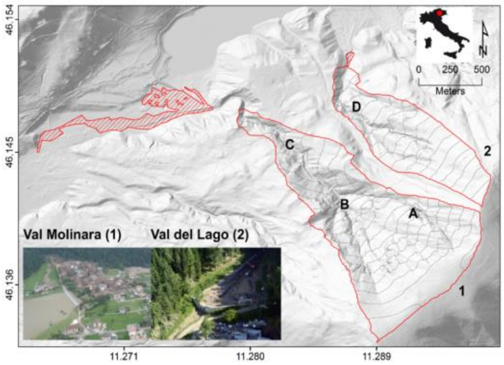

Fig. 1. Molinara and Val del Lago catchments (contour lines interval of 50 m); the crossed polygons represent the debris-flow deposits. A,B,C and D indicate the location of the photos in the Figure 2.

Fig. 2. Photos of the debris-flow torrents in the upper reaches (A), middle reaches (B), and lower reaches (C and D); field traces are highlighted in B and D.

On the 14th of August 2010, a storm hit the study area at 2:45 p.m. (CEST time) and continued until 5:00 a.m. of the following day, discharging a cumulated rainfall amount of 169.1 mm (rain gauge located 5 km from the two catchments). The bulk of the storm affected the area from 11:45 p.m. to 4:45 p.m. and was characterised by two main bursts of rainfall lasting two hours: maximum 1-hour rainfall intensity of 39.3 mm and 38.2 mm, separated by 45 minutes of low-intensity rainfall. The return period of the event was estimated equal to 100 years for the 3-hour maximum rainfall (73.1 mm) and greater than 200 years for the 6-hour maximum rainfall (156.3 mm). During the first storm, the basin hillslopes were partially saturated, due to previous rainfalls, and the debris-flood discharge increased considerably. During the second rainfall burst, massive destabilisation originated from the channel heads and triggered debris-flow surges in both basins. The surges progressively entrained sediment from the channel bed, enlarging in this way the debris-flow volumes. The Val del Lago debris flow filled the retention check dam (Fig. 1), whereas the Molinara torrent debris flow flooded the village of Campolongo di Pinè damaging roads and houses (Fig. 1). After-event field inspections did not indicate particular sediment source areas other than the channel heads and the subsequent channel reaches eroded by the debris-flow passage (Fig. 2).

3 Material and methods

The Val Molinara and Val del Lago debris flows were investigated by means of a field survey of the torrent reaches affected by the flow passage, available LiDAR surveys acquired before and after the event, correction of field survey through LiDAR data and statistical data analysis. Accounting for advances in debris-flow erosion [17] and event evidence, three basic conditions can be assumed. i) the channel bed was quite stable after the first storm, ii) the erosion depth Z (Fig. 2 and 3) was generated during the second highest debris-flow front (eyewitness of two surges), and iii) the average height of the debris flow front (Z_d) resulted from the difference between the average maximum flow depth (observed in the field in accordance with the top flow-width line joining opposite banks) and pre-event channel bed elevation (Fig. 3).

Accurate field investigations were conducted in the summer of 2011 estimating the sediment yield following the methodologies described by [5]. The torrent network was divided into homogeneous reaches in terms of slope, bed/banks morphology and sediment transport type. For each reach, representative cross-sections were measured (maximum of 3 sections) using a rangefinder (Disto Trupulse® 360B, precision 0.1 m and 0.1°). The shape of the section was approximated to a trapezium, and the following measurements were taken (Fig. 3):

- Top (B) and bottom (b) widths of the channel section where erosion and bank collapse occurred regardless of the traces of the debris-flow passage;
- Section heights of the right and left bank (Hr, Hl) corresponding to the maximum width of erosion B;
- Maximum cross-section flow widths (b) and heights (hr, hl) with respect to the post-event thalweg elevation, whose shape is clearly the result of the debris-flow passage. The channel bed average erosion (Z) was estimated in the surrounding reach of each cross-section by different types of field evidence (Fig. 2-D and Fig. 3) [18]. Afterwards, the following variables were calculated: the erosive yield rate Y (m^3/m), the eroded sediment volume (V) and the top-flow planimetric area Ac, determined through the B values.

Multi-temporal DTMs were provided by the Geological Services of the Trento Province and the difference between pre- and post-event digital surface models (DoD) allowed for the correction and validation of the field survey data. The pre-event DTM is the standard model of the Province acquired in 2006-2007 (mean density: 1.5 pts/m^2). The derived DTM has a 1-meter grid resolution with a vertical and horizontal accuracy of ± 0.30 m and ± 1.00 m respectively. The post-event DTM was obtained during an ad hoc flight (mean density: 10 pts/m^2) performed in the autumn of 2010. The DTM of 1-m grid resolution has a vertical and horizontal accuracy of ± 0.10 and ± 0.30 m respectively.

The resulting DoD could provide an error estimation of the ground differences between the pre- and post-event surfaces (Weathon et al., 2010). Nevertheless, the low resolution of the pre-event DTM and the significant irregularity of the banks made difficult a precise assessment of the local variation of the channel characteristics (*B* and heights of each bank *Hr*, *Hl*). The integration of remote sensing data with field survey was then necessary to generate the erosion-related variables (channel yield rate *Y* and volume *V*). In this context, we used the cross-section post-event surveys (Z, Z_d, *Hr*, *Hl*, *hr*, *hl*, *b*, *B*; assumed to be the more correct) as primary information and then we accounted for them to obtain an adjusted DoD based on matching the cross-section field surveys.

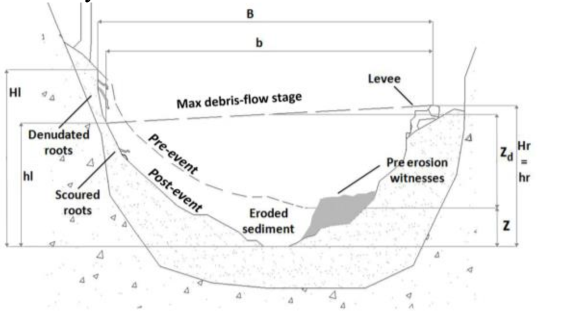

Fig. 3. Sketch of cross-section measurements with the main field evidences. Tiny letters indicate the variables of the flow traces, capital letters indicate the variables of the erosion evidences.

The analysis of the erosion depths (*Z*) has considered their statistical distribution with the aim to test the existence of a characteristic erosion pattern produced by a severe debris flow after a long period of inactivity. Data were tested both through continuous asymmetric probability distributions and a number of symmetrical distributions. In particular, following the suggestions of [19], the adaptation considered the exponential, logistics, Gumbel, Fuller and log-normal distribution and was completed applying the Kolmogorov-Smirnov test with a confidence level of 95%. The most appropriate distributions were selected by comparing the values of root mean square deviation (RMSD).

4 Results

In summer 2011, the field survey consisted of 190 cross-section measures in the Molinara catchment, corresponding to 155 homogenous reaches. Regarding the Val del Lago catchment, a total of 73 cross-sections, grouped into 45 homogeneous reaches were surveyed. The DoD calculation of debris-flow volume and depths of erosion for the Molinara torrent provided a volume of 68400 m^3 (with an error of the estimate: $Err_{v,high}$ = 13 100 m^3, [7]) and 8700 m^3 ($Err_{v,high}$ = 2700 m^3) in the Val del Lago catchment. Both DoD volumes were substantially confirmed by the post-event surveys of the Torrent Control Service (Trento Province authority). Afterwards the average erosion depths from the field survey and LiDAR analysis were compared. The analysis highlighted that field observations have systematically underestimated the erosive depths, evidencing a linear correlation between field (Z_{Field}) and DoD values (Z_{DoD}). Underestimation was significant and can be expressed by the following equation:

$$Z_{DoD} = \frac{Z_{Field}}{q} \qquad (1)$$

where the coefficient q showed a value of 0.39 for Molinara (p value < 0.01, R^2 = 0.46) and 0.44 in Val del Lago (p value < 0.01, R^2 = 0.49). Thanks to equation 1 the final correct depths of erosion reached maximum values (Z_{max}) of 4.86 and 3.74 m in the Molinara and Val del Lago torrents respectively.

The analysis of the datasets of erosion depth (*Z*) indicated that are significantly skewed with a long tail for the largest values. The *Z* sample characteristics in terms of the cumulative distribution function (CDF) are shown in Fig. 4a, where the variable has been normalised to the dimensionless depth: $Z_r = Z/Z_{max}$, being Z_{max} the maximum *Z* measured in each stream. The Z_r sample has proven not to be adaptable to the exponential and logistic probability distributions (Kolmogorov-Smirnov test, confidence level of 95%), while it resulted adaptable to all three right-skewed distributions. Comparing the measured *Z* values with those expected from the CDF of the log-normal, Fuller and EV1 distributions, the latter was the most accurate (RMSD equal to 0.22 and 0.17 for the Molinara and Val del Lago basins, respectively). Afterwards, the hypothesis that the datasets of the two basins belonged to the same population was tested focusing on the dimensionless erosion depth. The statistical analysis used the non-parametric Mann-Whitney test (95% confidence level) assuming the null hypothesis corresponding to samples with equal distribution (Gumbel, Fuller, log-normal), and the alternative hypothesis to samples with different distributions. The analysis proved that the Z/Z_{max} values of the adjacent catchments belong to the same population with a p-value << 5%. The joint Molinara-Val del Lago Z_r sample (176 values) has an average of 0.308 and a standard deviation of 0.228. This sample has been shown to follow an extreme value EV1 (Extreme Value Type I) probability distribution at best (Fig. 4b). The function of the cumulative probability (*P*) of non-exceedance can then be written as:

$$P = e^{-e^{-y}} = e^{-e^{-\alpha\left(\frac{Z}{Z_{max}}-\mu\right)}} \qquad (2)$$

where *y* is the reduced variable of the distribution and the parameter estimation (method of moments) yields: α= 5.628 and μ=0.206.

The corrected adaptation of the sample to the EV1 probability distribution was positively verified even by means of [20] test assuming a confidence level equal to 95%. Equation (2) was then tested to recalculate the eroded volume V_e through the assumption of a number (*n*) of equal-spaced $Z_{r,i}$ (=Z_i/Z_{max}) intervals as follows:

$$V_e = \sum_{i=0,n}\left(p_{r,i} Z_{r,i} Z_{max} L b_m\right) \qquad (3)$$

where $p_{r,i}$ is the relative probability density (Equation 2) associated with the normalised erosion rate $Z_{r,i}$ of the *i-th* interval, *L* is the total length of the erodible channels and b_m the mean torrent width. The computation of V_e assuming 10 equal intervals of Z/Z_{max} (class width of 0.1) provided values of eroded material equal to 63000 m^3 in the Molinara channel and 8000 m^3 in the Val del Lago reach. These volumes do not vary significantly with an increase in the number n of the intervals (i.e., 13% reduction in volume for n=100) and substantially agree with those calculated through DoD analysis.

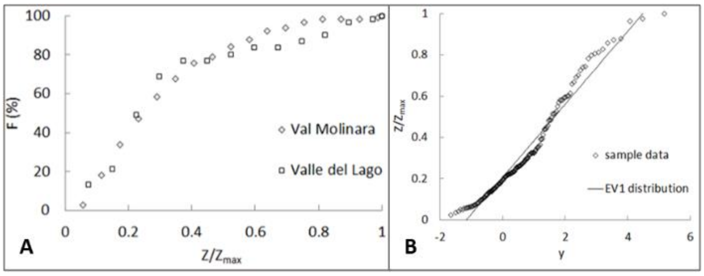

Fig. 4. a) Cumulative frequency (*F%*) distribution of the normalised depth of erosion (Z/Z_{max}); b) probabilistic plot and adaptation line (Equation 2) to the EV1 distribution: reduced variable y versus Z/Z_{max}.

5 Discussion and conclusions

The mobilised sediment volumes in the triggering areas were negligible compared to the final magnitudes. The investigated two adjacent debris flows were dominated by in-channel sediment entrainment, equal to 68400 and 8700 m^3 in the Molinara and Val del Lago basins respectively. The maximum erosion depths (4.9 m and 3.7 respectively) are comparable to those found by [8,10].
According to [21], long silent periods have been confirmed as preparation for important sediment recharge, particularly for the geological settings of volcanic and compact metamorphic rocks. When the hazard has to be assessed in these low-frequency/apparently stable mountain streams, the difficulty of the geomorphic estimates of the expected sediment volumes makes the identification of a statistical erosion pattern a practical and valuable tool. As already shown by [8], the distribution of the erosion depth Z has been confirmed to be markedly asymmetrical towards the right tail. Starting from the scale of the expected maximum deepening of the bed (Z_{max}), recalculating the volume - accomplished by means of the fitting probability distribution EV1 (Equation 2) and a simplified sediment budget (Equation 3) - has proven to be very precise, requiring only a few data. The computation for the Molinara/Val del Lago basins has obviously benefitted from the back-analysis and thus from the Z_{max} field measurement, and parameter (α and μ) adaptation. Nevertheless, the computational method could be quite promising and innovative when used in a purely predictive task. Indeed, assuming the channel length to be invariant under erosion and the average channel width quasi-invariant, Z_{max} could be measured by carrying out geophysical surveys to estimate the sediment thickness. A certain degree of subjectivity would remain in the distribution parameters but the proposed model for real cases and their comparison with the measurable values of bank heights before the event would help to make a reliable choice. Additional verifications are then recommended, in terms of the number of events (e.g., monitored cross-sections within a network of experimental debris-flow catchments) and spatial continuity of the information provided by intensive post-event surveys.

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