Rainfall and debris flow occurrence in the Moscardo basin (Italian Alps)

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ABSTRACT: The Moscardo Torrent is a small mountain stream in the Italian Alps and presents a high frequency of debris flows. The basin has been monitored since 1989 and both rainfall data and debris flow occurrence have been recorded, these latter through ultrasonic gauges. This paper aims at giving a new contribution on the long debated question of the cause-effect link between rainstorms and debris flow triggering. A sample of 73 rainstorms 15 of which caused debris flows is considered in this study. The main characteristics of rainstorms (total rainfall amount, duration, average and 60 minutes maximum intensity) and antecedent precipitation are analysed. In the Moscardo basin comparatively low-intensity storms are sufficient to trigger debris flows. The results are compared with those of some well-known works on this topic and lead to conclude that, even in a single small basin, rainstorm characteristics play an important role but are not exhaustive in defining debris flow initiation conditions.

1 INTRODUCTION

Precipitation is probably the easiest to measure amongst the factors that affect debris flows triggering: rainfall data associated with debris flow occurrence are often available and reported in scientific and technical literature. A number of contributions analyses the effect of rainfall in triggering debris flows and shallow landslides (De Vita & Reichenbach 1998): a basic distinction (Terlien 1998) can be made between studies aimed to define empirical rainfall thresholds for instability phenomena or to perform a statistical analysis of rainstorm parameters influencing debris flow initiation, (e.g. Caine 1980, Innes 1983, Govi et al. 1985, Cancelli & Nova 1985, Blijenberg 1998) and deterministic modelling of the hydrological conditions controlling debris flow occurrence (e.g. Johnson & Sitar 1990, Montgomery & Dietrich 1994, Wilson & Wieczorek 1995).

Rainfall data available for studies on debris flows in the Alpine range are usually derived from standard rain gauge networks: these data are suitable for the analysis of storms causing widespread debris flows at regional scale. However, given the large dimensions of the mesh of their network, they often fail to characterise spatially-limited cloudbursts which trigger debris flows in small basins. This paper aims to examine the relations between rainfall characteristics and debris flow occurrence at local scale, focusing on a small alpine basin expressly instrumented for rainfall and debris flow monitoring.

2 FIELD SITE

The Moscardo Torrent is a small stream in the Eastern Italian Alps (Figs 1 and 2); its basin drains an area of about 4 km^2 ranging in elevation from 890 to 2043 m. The rocky substratum of the Moscardo basin is made of Carboniferous flysch, represented by highly fractured and weathered shale, slate, siltstone, sandstone and breccia. Quaternary deposits, mostly consisting of scree and landslide accumulations, are common in the basin. Most of the basin slopes are covered by a dense coniferous forest; a vast bare area, partly lying above the tree line, is however present in the upper part of the basin. Here, the presence of a deep-seated gravitational deformation, the low rock mass quality and its highly shattered state make the very steep slopes of the basin prone to widespread rockfalls and shallow slope failures which supply large amounts of debris to the channel (Fig. 3). The initiation area of debris flows is indicated in Figure 2; initiation points can vary from event to event, being located in the main channel; typical gradients in the initiation area are of 20° to 30° for the main channel and of 30° to 50° for channel banks and hillslopes. The source material consists of scree deriving from weathering and wasting of rocks. The size of particles ranges from clay to coarse rocky fragments; fine material (silt and clay) averages 20-25% of debris matrix (<32 mm). The rheological characteristics of debris flow material were analysed in a previous paper (Coussot et al., 1998). Anthropogenic influence on debris flow activity in the Moscardo torrent is limited to some check dams which are intended to prevent bed erosion and to stabilize channel banks in the middle and lower stretches of the main channel.

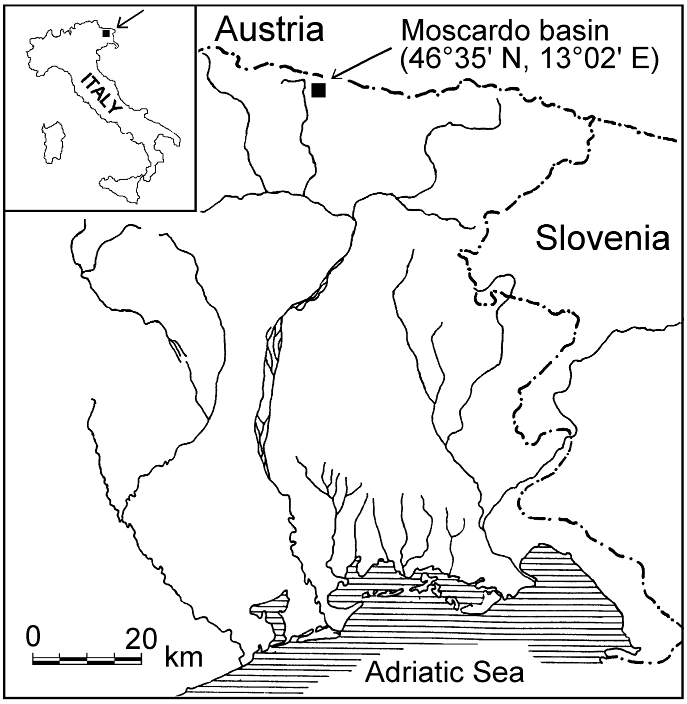

Figure 1. Geographical location of the study basin.

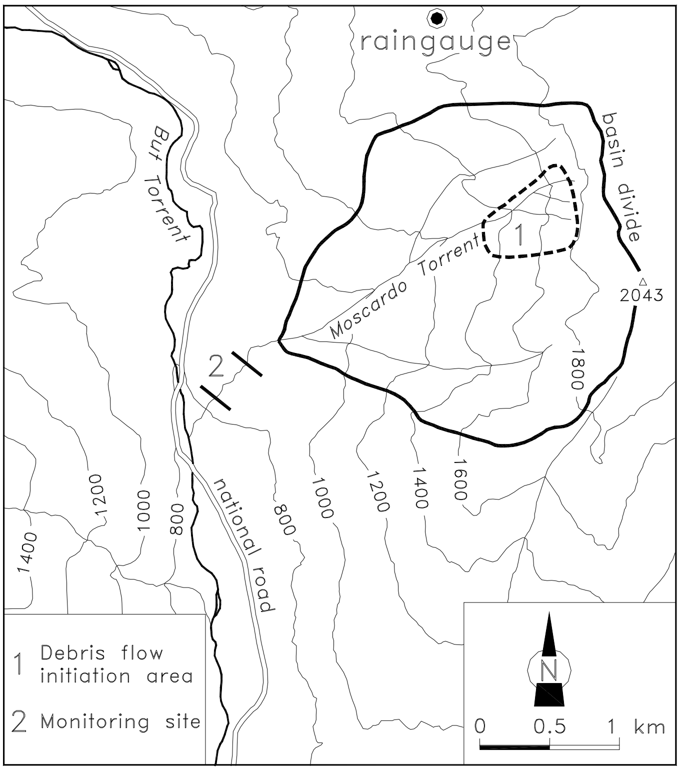

Figure 2. Map of the Moscardo basin.

The climatic conditions of the Moscardo basin are typical of the easternmost part of the Italian Alps, with abundant precipitation throughout all the year, cold winters and mild summers. Precipitation in the study region is caused by cyclonic and local storms, both influenced by local orographic conditions. Average annual precipitation amounts to 1660 mm with 113 rainy days per year; the highest rainfall occurs in October and November with monthly values averaging 170 - 180 mm; summer months are characterised by average monthly rainfall amounting to 150 - 170 mm. Comparatively low-precipitation occurs during winter with monthly values of 80 - 100 mm. Precipitation mostly occurs as snowfall from November - December to March - April.

Figure 3. Debris flow initiation area in the Moscardo Torrent.

Because of the high frequency of debris flows (from one to four events per year in the last decade), the Moscardo Torrent was selected in mid-eighties for debris flow monitoring. The monitoring system which was installed in 1989 to record the passage of debris flow waves is based on ultrasonic sensors installed in mid-fan area; precipitation is measured by a digital rain gauge installed at an elevation of 1520 m, at about the average catchment altitude, close to the basin divide (Fig. 2). Rainfall data recorded from 1990 to 1998 have been considered in this study. During this period, 15 debris flows have occurred; the hydrographs of most of them have been recorded by the installed gauges (Arattano et al. 1997); for some events only the rainfall and time of occurrence are available.

Here we characterise the relations between precipitation and debris flow initiation in which rainfall data can be deemed representative of water influx while the time of occurrence of individual debris flows is known from instrumental records.

3 RAINFALL DATA AND DEBRIS FLOW OCCURRENCE

The following variables were selected for the analysis of rainstorms in the Moscardo Torrent: accumulated rainfall (mm), storm duration (h), average storm intensity (mm h^{-1}) and 60 minutes maximum intensity (mm h^{-1}). As already proposed by various authors (Cannon & Ellen 1985, Wieczorek 1987, Govi & Sorzana 1980, Honglian & Xiangxing 1988) the rainfall which preceded the rainstorms was used as an indicator of the moisture content of the sediments: four different periods as long as 24 hours, 5, 10 and 15 days were chosen.

The rainfall data were analysed to characterise the typical debris flow triggering rainstorms. Debris flow events in the Moscardo Torrent were observed during rainstorms which had a minimum of 21 mm of total rainfall (measured at the time of debris flow occurrence at the gauging stations) and at least a 60 minutes rainfall intensity of 12.6 mm h^{-1}. Moreover debris flows occurred in correspondence to the maximum rainfall intensity in 13 out of 15 cases. From these characteristics a criterion was established for selecting significant storms in the available rainfall records: rainstorms exceeding 20 mm of total rainfall (cumulated up to the time in which the maximum 60 minutes intensity was reached) and a 60 minutes maximum intensity of 10 mm h^{-1} have been defined as a potential debris flow triggering rainstorm and were therefore selected for the analysis. Besides, rainstorms were considered distinct events when separated by at least 6 hours with no significant precipitation (≤ 0.2 mm). This relatively short time was chosen to take into account the high intensity and short duration storms which triggered debris flows in 5 out of 15 considered events; moreover, 6 hours with no rainfall are sufficient to induce the recession of the flood water stage which could be associated to debris flow initiation in the Moscardo Torrent. In this way 73 rainstorm events recorded from 1990 to 1998 were considered in the study, 15 of them triggered a debris flow. From debris flow hydrographs recorded in the Moscardo Torrent (Arattano et al. 1997), a travel time of about 5 to 10 minutes from the initiation area to the channel reach instrumented with ultrasonic gauges can be estimated: this time lag has a negligible influence on the selection of rainfall records.

Debris flows in the Moscardo Torrent are concentrated in summer months: the earliest recorded event occurred on June 22; the latest on September 30. The seasonal distribution of debris flows approximately follows that of intense storms: 80 % of observed debris flows and 73 % of selected rainfall events occurred from June 15 to the end of August. Although total precipitation in autumn is often very abundant (e.g. a daily rainfall of 193 mm in a day, on November 11, 1992), no debris flows occurred in October and November since 1989. This can be referred both to the infrequent occurrence of high intensity storms and to the scarcity of sediment (mainly scree and weathered rock) available for mobilisation after the summer activity of debris flows: the long lasting, low to medium intensity autumnal rainfall results in the erosion and fluvial reworking of debris flow deposits accumulated in downstream channel stretches, giving rise to bedload or hyperconcentrated transport. Also in springtime intense cloudbursts seldom occur in the study area (only 5 storms from May 1 to June 15).

4 ANALYSIS AND DISCUSSION

Two rainstorm groups (hereafter referred to as debris flows and no debris flows) were compared by means of the t-test with separate variance estimate and the nonparametric Mann - Whitney U test: the results are presented in Table 1.

Table 1. - Comparison of storm variables.

	Mean	Std. Dev.	*p* t-test	*p* U test
Total storm rainfall (mm)			< .01	< .01
No debris flows	29.2	19.1		
Debris flows	55.0	33.0		
Storm duration (h)			0.12	0.13
No debris flows	7.8	9.4		
Debris flows	14.3	14.6		
Average storm intensity (mm h^{-1})			0.33	0.61
No debris flows	7.0	5.4		
Debris flows	9.7	9.9		
60 minutes max. intensity (mm h^{-1})			< .01	< .01
No debris flows	17.1	7.9		
Debris flows	27.9	8.3		
Antecedent 24 h rainfall (mm)			0.55	0.14
No debris flows	4.0	8.3		
Debris flows	5.8	10.4		
Antecedent 5 days rainfall (mm)			0.83	0.90
No debris flows	30.4	31.7		
Debris flows	28.7	24.2		
Antecedent 10 days rainfall (mm)			0.81	0.72
No debris flows	60.0	49.0		
Debris flows	56.6	48.2		
Antecedent 15 days rainfall (mm)			0.76	0.64
No debris flows	96.8	64.3		
Debris flows	91.1	63.7		

Both tests indicate that, for $p = 0.01$, total event rainfall and 60 minutes maximum intensity are higher for the storms which caused a debris flow than for the storms that did not trigger debris flows. No significant differences arise for the remaining variables (Table 1). A discriminant analysis aimed to determine which variables better discriminate between two groups was not performed because some of the assumptions required by this method were not met.

Figure 4 shows the relationship between two variables (accumulated event rainfall and 60 minutes maximum intensity) whose values are significantly higher in debris flow storms than for no debris flow storms. Ellipses superimposed to the scatterplot are centered on sample mean with horizontal and vertical projections onto the X and Y axes equal to the mean ± (range·0.5), where range and means refer to the two plotted variables; the orientation of the ellipses depends on the linear relationship between accumulated rainfall and 60 minutes maximum intensity. Although this plot is not suitable to define a threshold separating debris flow storms from no debris flow ones, it clearly shows the substantially different distribution of the considered variables in two groups.

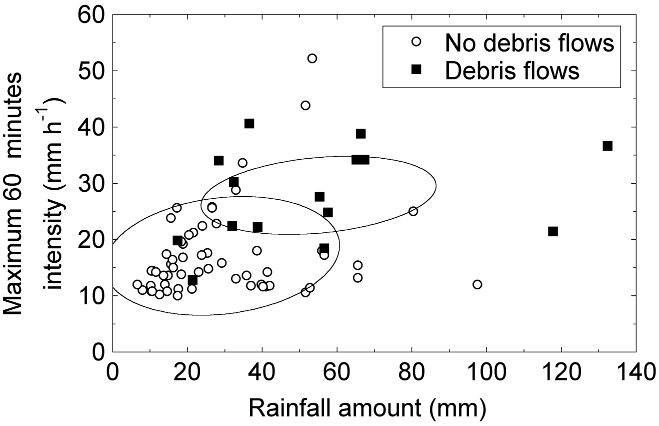

Figure 4. Relationship between total storm rainfall and 60 minutes maximum intensity.

A «classic» representation of rainstorm characteristics affecting the triggering of debris flows and shallow landslides is a scatterplot of rainfall intensity (or cumulative rainfall) versus storm duration, in which empirical threshold lines define critical conditions for debris flow initiation (e.g. Caine 1980, Innes 1983, Cannon & Ellen 1985, Wieczorek 1987, Larsen & Torres-Sánchez 1998). In Figure 5 the line #2 delimits the lower envelope of debris flow causing storms. A separation between debris flow and no debris flow storms cannot be defined: the critical line of debris flow rainfall defines the duration - intensity combination which is necessary, but not sufficient, to trigger debris flows in the Moscardo Torrent. The equation of the threshold line for the Moscardo Torrent (Fig. 5) is:

$$I = 15 \cdot D^{-0.70} \qquad (1)$$

where I is the average storm intensity (mm h^{-1}) and D storm duration (h). When compared to the critical line of Caine (1980) (line #5 in Fig. 5), the Moscardo Torrent line corresponds to a threshold with similar intercept and a higher negative slope; these are respectively lower and higher than Ceriani's ones (line #4 in Fig. 5). Lower critical values in the Moscardo basin can be inferred by the fact that the thresholds proposed by the quoted authors refers to data collected world-wide and corresponding to the rainfall necessary to induce shallow instability on undisturbed slopes (Caine 1980), or to catastrophic debris flows at regional scale in the mountainous area of Central Italian Alps (Ceriani et al. 1994) whereas in the Moscardo basin, due to critical topographic conditions and physical and mechanical characteristics of debris, comparatively low-intensity rainfall is sufficient to provoke debris flows. The threshold found by Wieczorek (1987) in a study site of 10 km^2 in California is closer to the Moscardo critical line with the exception of the shortest duration. The critical line proposed by Wieczorek (1987) (line #1 in Fig. 5) is based on storms that caused as few as one debris flow in a spatially-limited study site: the extent of the study area and the detail in analysing individual events are similar to those of the present study: it is not surprising that obtained rainfall thresholds are less than those developed for abundant or catastrophic debris flows at larger space scales.

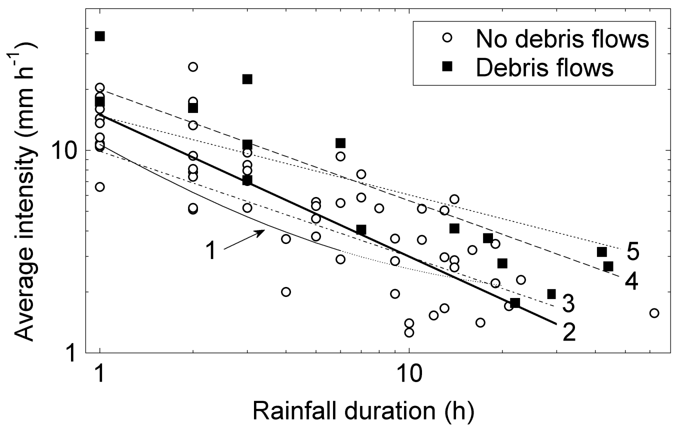

Figure 5. Relationship between storm duration and average intensity: 1 Wieczorek (1987); 2 Moscardo Torrent (this study); 3 Montgomery et al. (in press); 4 Ceriani et al. (1994); 5 Caine (1980).

The threshold line obtained by Montgomery et al. (in press) (line #3 in Fig. 5), refers to a recently clear-cut logged basin in coastal Oregon (USA), since the basin is highly disturbed, its critical rainfall is lower than the Moscardo one for short duration and similar for longer duration.

As discussed above, the plot of average intensity versus time does not allow one to unequivocally separate debris flow from no debris flow storms; a graph of 60 minutes max intensity versus duration did not give a better result. A clearer separation can be obtained by introducing the 60 minutes maximum intensity as a third variable (Fig. 6).

Antecedent precipitation was analysed in relation to storm parameters by means of graphical and statistical tools. Antecedent rainfall of 24 hours, 1, 5, 10 and 15 days does not help to distinguish between debris flow-causing and debris flow-non-causing storms. This can be referred to the absence of significant differences in antecedent precipitation between debris flow and no debris flows storms (Table 1). Moreover, a number of springs present along the main channel and the melting of snow avalanche accumulations contribute to the high moisture content of sediments during summer in the Moscardo basin, reducing the importance of rainfall which precedes intense storms. This can partly explain the debris flow triggered by low maximum intensity and duration, although it's impossible to separate the role of springs and snowmelt from that of rainfall.

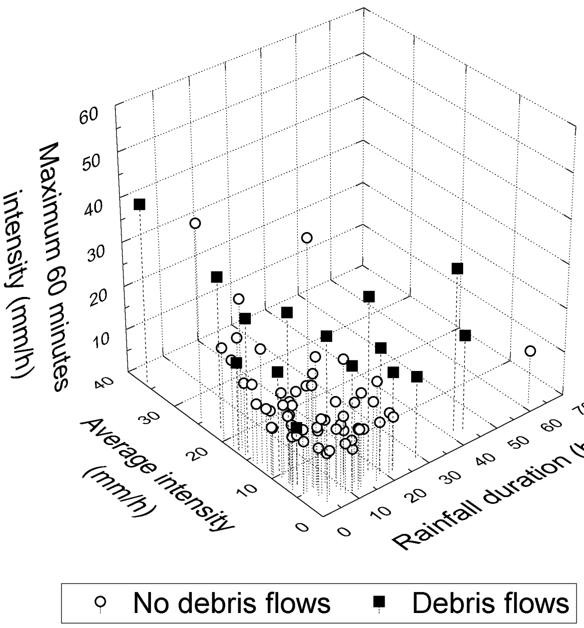

Figure 6. 3D scatterplot of storm duration, average intensity and 60 minutes maximum intensity.

On the other hand, the occurrence itself of a debris flow may influence in different ways the possibility of further debris flows in the following days and weeks, increasing the complexity of the relations between rainfall and debris flows. The most obvious consequence of a debris flow is the removal of sediment available for mobilisation: the probability of new debris flows in the subsequent period would be lower even in the case of high intensity rainstorms; for instance, the two highest 60 minutes intensity recorded rainfall (52.2 mm h^{-1} on August 28, 1997 and 43.8 mm h^{-1} on June 28, 1998) did not trigger a debris flow and occurred respectively 35 and 5 days after a debris flow. However, abundant deposits are sometimes left by debris flows in upper channel stretches, often after travelling only 200 - 300 m, as it resulted from field surveys. These deposits can be mobilized even by a non exceptional rainfall: in such cases previous debris flows do not reduce but even increase the probability of a new event like it happened in 1993, when a debris flow occurred on July 11 and was followed by two more events within ten days. Finally, a rainstorm can trigger a debris flow which could stop along the main channel before reaching the monitoring instruments which are located in the lower part of the channel (Fig. 2).

5 CONCLUSIONS

Rainstorms that triggered debris flows in a small instrumented catchment were compared with rainstorms that did not trigger any debris flow on the basis of nine years of observations. Storms which triggered debris flows display higher accumulated rainfall total and 60 minutes maximum intensity than those which did not trigger a debris flow. In Figure 5, an empirical line delimiting the lower threshold of debris flow occurrence was drawn; in this graph, however, storms belonging to two groups (causing and not causing a debris flow) show a vast common area: a simple distinction of two storm groups is not possible; even the analysis of antecedent precipitation does not improve the storm classification.

The preceding analysis confirms the complexity of the processes controlling the triggering of debris flow even in a single, small basin: a critical combination of sediment availability and hydrologic conditions is necessary to cause debris flow formation. The study of rainstorm characteristics plays an important role but is not exhaustive in defining debris flow initiation conditions. This is particularly true when sediment moisture is influenced by a complex groundwater flow regime and sediment availability depends on bank and slope failures, as well as on the previous occurrence of debris flows, like it occurs in the Moscardo basin.

The consequent difficulty in discriminating between storms which trigger and do not trigger debris flows on the basis of rainfall parameters represents a major shortcoming in the design of a debris flow warning system based only on rainfall measurement or on quantitative rainfall forecasts in the torrents. Rainfall-based, real-time warning systems for debris flows have been successfully developed under other morphoclimatic conditions (Wilson et al. 1993, Zhang 1993). However in the Moscardo Torrent and in similar small alpine streams, because of the high probability of false alarms, such a warning system could be at most intended to trigger a pre - alarm state for civil protection officers, not to spread a general alarm to the public.

A better understanding of debris flow initiation processes, as well as improved prospects for the development of warning systems could come from the installation of proper instrumentation, such as piezometers, in debris flow initiation areas (Johnson & Sitar 1990, Wilson & Wieczorek 1995, Genevois et al., in press). Piezometric measurements coupled with rainfall data could also provide an input to hydrological models aimed to simulate flow conditions controlling debris flow initiation. In the Moscardo Torrent, the main problem concerning the instrumentation of the debris flow initiation area is that it is located in a very steep gully affected by frequent rockfall, shallow landslides in debris-covered slopes and bank failures (Fig. 3), where the installation and maintenance of a piezometric monitoring system is practically impossible.

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