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# Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps)

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**Abstract**

Field data on debris flows are of utmost importance for improving knowledge of these hazardous phenomena and for the development of attenuation measures. In alpine basins, debris flows generally occur with a frequency high enough to create serious risk to human settlements and transportation routes, but too low to justify monitoring activity capable of providing enough data in a sufficiently short time. The Moscardo Torrent, a small stream in the Eastern Italian Alps, is an exception to this general situation since it displays a high frequency of debris flows (commonly at least one event per year). In 1989, this torrent was instrumented and the results of the following 10 years (1989–1998) of debris-flow monitoring are presented, with an analysis of collected data. The equipment installed allowed measurement of rainfall, flow stage and ground vibrations caused by debris flows. Other important debris-flow variables, that is, mean front velocity, peak discharge and flowing volume were estimated from instrumental records. Video pictures have proved to be useful for the visual interpretation of debris-flow waves and have made it possible to estimate the surface velocity of debris flows. Recorded data are compared with other experimental data sets collected and documented worldwide. Advantages and shortcomings of different types of sensors are discussed with relevance both for research monitoring purposes and for possible use in debris-flow warning systems. 

*Keywords:* Debris flow; Monitoring; Hydrograph; Velocity estimation; Alpine basin

## 1. Introduction

The aim of this paper is to summarise 10 years (1989–1998) of field research in the Moscardo Torrent, a debris-flow prone basin in the Eastern Italian Alps. The monitoring system and its improvements made over a decade are described. An analysis of debris-flow characteristics is also presented on the basis of the experimental data that have been gathered.

Important and well-known monitoring activities on debris flows have been carried out in several geographical regions of the world (e.g. Okuda et al., 1980; Watanabe and Ikeya, 1981; Pierson, 1985, 1986; Johnson and Sitar, 1990; Zhang, 1993; Suwa et al., 1993, 2000; Marcial et al., 1996). In alpine basins, short duration and relatively low frequency of debris flows make both direct field measurements performed by local operators and monitoring activities carried out through permanently installed equipment very difficult and costly. Monitoring activities, in particular, become worthwhile only if enough data can be recorded in a

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sufficiently short period of time. In the mid-eighties, the Institute for Hydrological and Geological Protection of the Italian National Research Council (CNR IRPI) of Torino started a research project intended to design and install a monitoring system in a small stream in the Italian Alps. The Moscardo Torrent appeared to be suitable for the installation of a debris-flow monitoring system because it displayed a high frequency of debris flows (commonly at least one event per year) and had several other favourable characteristics. The frequency of debris flows in the Moscardo Torrent is decidedly lower if compared to some Asian catchments, for example, Jiangjia Gully in China (Zhang, 1993) or Mt. Yakedake (Suwa et al., 1993), but is unusually high for the European Alps. The Moscardo Torrent was instrumented for debris-flow monitoring in 1989; the research was then continued in collaboration with the CNR IRPI of Padova.

In the first years, the Moscardo Torrent measuring system represented a pioneering site for debris-flow monitoring in Europe. Recently, more alpine basins have been instrumented for debris-flow measurement in Italy (Genevois et al., 2000) and in Switzerland (Rickenmann et al., 2001). Other recent monitoring experiences in Europe are based on rainfall simulation and on artificially triggered debris flows: Blijenberg et al. (1996) carried out hydrological observations and rainfall simulations in the initiation zone of a debris flow in the French Alps; Bonte (2000) described debris flows triggered through the artificial saturation of cohesive glacial deposits on a hillslope of the Lainbach basin (Germany).

## 2. Study basin

The Moscardo Torrent basin was chosen for debris-flow monitoring for the following reasons:

- high frequency of debris-flow occurrence;
- easy accessibility to the fan, with availability of electric power;
- a well-defined channel on the fan, not subject to serious avulsions.

A map of the Moscardo Torrent basin is shown in Fig. 1; the main morphological parameters of the basin above the fan apex are listed in Table 1. The rocky

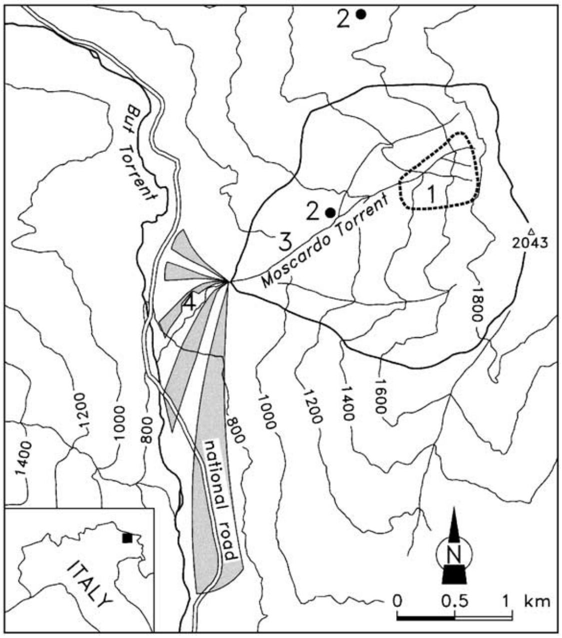


Fig. 1. The Moscardo Torrent basin and its alluvial fan. (1) Debris-flow initiation site; (2) rain gauges; (3 and 4) instrumented channel stretches.

substratum of the basin is made of Carboniferous flysch, represented by highly fractured and weathered shale, slate, siltstone, sandstone and breccia (Spalletta et al., 1979). Quaternary deposits, mostly consisting of scree and landslide accumulations, are common in the basin. The presence of a deep-seated gravitational deformation at the valley head, the low rock mass quality and its highly shattered state make the steep slopes of the basin prone to rockfalls and shallow slope failures which supply large amounts of debris to the channel. The aerial photo of the basin (Fig. 2) shows the presence of vast sediment source areas in the upper part of the basin and along the main channel. The initiation area of debris flows is indicated in Fig. 1. Initiation points can vary from event to event, generally being located at the head of the main channel; typical gradients in the initiation area are of 20°–30° for the main channel and of 30°–50° for channel banks and hillslopes. The source material consists of scree deriving from the weathering and wasting of rocks.

The Moscardo Torrent has formed a huge, asymmetrical fan that spreads across the valley floor, forcing the main stream (But Torrent) to the toe of the

Table 1
Main morphometric parameters of the Moscardo Torrent basin above the fan apex

| Basin area ($km^2$) | Maximum elevation (m) | Minimum elevation (m) | Average basin slope (%) | Main channel length (km) | Average main channel slope (%) |
|---|---|---|---|---|---|
| 4.1 | 2043 | 890 | 63 | 2.76 | 37 |

opposite valley slope. The fan extends southward for about 2.7 km (Fig. 1) and covers an area of 1.46 $km^2$; it has a composite slope ranging from 7°–8° at the proximal part and 4°–5° in the lower area; the fan surface is characterised by alternation of elongated old levees and lobe deposits.

The Moscardo debris-flow deposits are poorly sorted and show a wide granulometrical distribution (Moscariello and Deganutti, 2000). Lateral levees and debris-flow lobes consist mostly of pebbles and medium to fine boulders supported in a muddy matrix; larger boulders with an intermediate diameter of 2–3 m are also common. The particle-size distribution of debris-flow deposits, obtained from several samples taken in lobe deposits and along the main channel, is shown in Fig. 3.

Most of the basin slopes are covered by coniferous forest (64% of basin area) and mountain shrubs (18% of basin area); a bare area (tussock, scree and outcropping rocks) is present in the upper part of the basin and along the main channel and occupies 18% of the catchment area. Although its area is limited in comparison to vegetation-covered slopes, bare ground provides most of the debris supplied to the channel network. Anthropogenic influence on debris-flow activity in the Moscardo Torrent is limited to nine concrete check dams, which are intended to prevent bed erosion and to stabilise channel banks in the middle and lower stretches of the main channel. Forest areas do not display evidence of erosion: disturbance due to logging is limited and does not significantly contribute to sediment supply from basin slopes to the channel network.

The climatic conditions of the Moscardo basin are typical of the easternmost part of the Italian Alps, with abundant precipitation throughout the year, cold winters and mild summers. 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

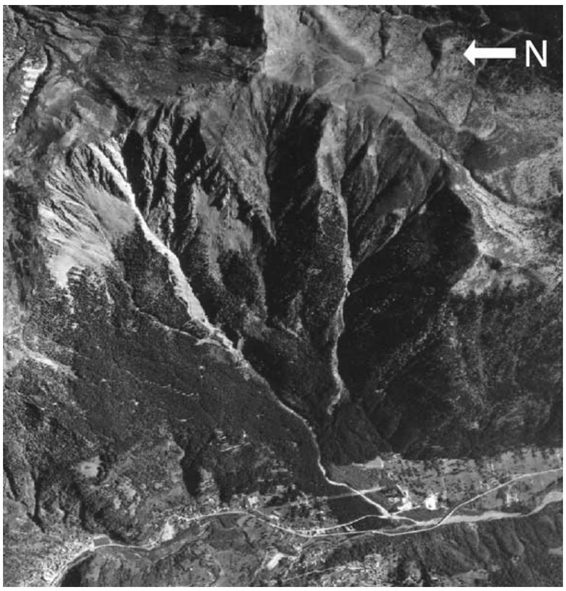


Fig. 2. The Moscardo Torrent basin (aerial photo taken in 1986).

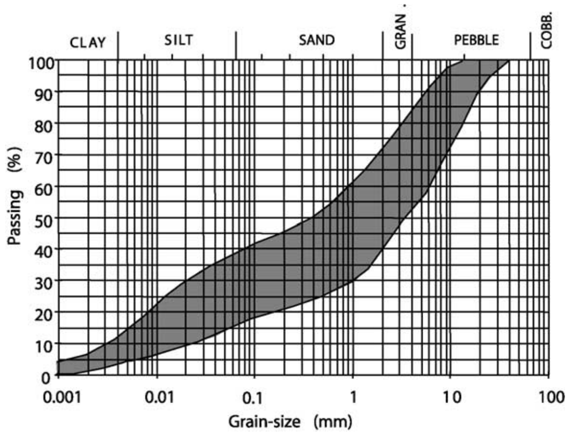


Fig. 3. Particle-size distribution of the debris-flow deposits. The shaded area encompasses grain size curves from 10 samples (grain size <40 mm).

months are characterised by an average monthly rainfall amounting to 150–170 mm. Precipitation from November–December to March–April occurs mostly as snowfall; winter is the driest season with monthly values of 80–100 mm.

Debris flows in the Moscardo Torrent take place in the summer months: the earliest event recorded from 1989 to 1998 occurred on June 22, the latest on September 30. Although total precipitation in autumn is often very abundant, no debris flows occurred in October and November, at least since 1989. This could be due both to the infrequent occurrence of high-intensity storms during these months and to the scarcity of sediment available for mobilisation after the occurrence of summer debris flows: the long-lasting, low to medium intensity, autumnal rainfall results in the erosion and fluvial reworking of debris-flow deposits accumulated along the main channel, giving rise to intense bedload transport.

## 3. The monitoring system

In 1989, a monitoring system consisting of two ultrasonic sensors and a rain gauge was set up in the Moscardo Torrent. The rain gauge was installed close to the basin divide at an elevation of 1520 m, which is about the average catchment altitude (Fig. 1). Two ultrasonic sensors were installed in mid-fan area on a channel stretch 300 m long, with an average slope of 10%. In 1995, the ultrasonic sensors were replaced by new ones and a third ultrasonic sensor was placed further upstream, extending the total length of the monitored channel reach to 370 m. A fixed video camera was positioned close to the intermediate of the three ultrasonic sensors and a network of four seismic detectors was set up about 1 km upstream from the ultrasonic gauging stations (Fig. 4). Video recordings are triggered by means of software, which detects abrupt changes in stage values recorded by the upstream ultrasonic gauge. In 1997, a second rain gauge was installed in the centre of the basin and two new seismic sensors were set up on the fan close to the intermediate ultrasonic gauge.

As a result of torrent control works, monitoring activities in the Moscardo Torrent were almost completely suspended in 1998 and 1999 and limited to field surveys and rainfall measurements. In 1999, some tests to compare the performance of seismic sensors with that of sonic sensors provided by a Japanese University (Itakura et al., 2000) were also carried out on the fan of the torrent.

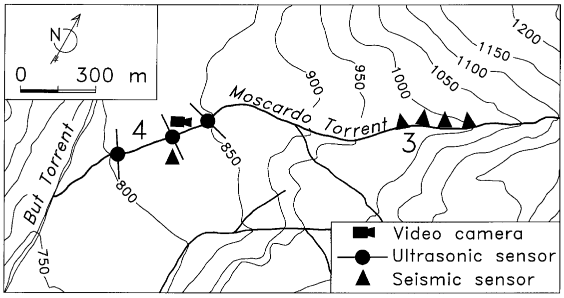


Fig. 4. Plan view of the instrumented channel stretches. (3 and 4) Sites location shown in Fig. 1.

### 3.1. Uses of the different sensors and resulting estimations

#### 3.1.1. Rain gauges

A number of studies analyse the role of rainfall in triggering debris flows and shallow landslides (De Vita and Reichenbach, 1998). Given the large dimensions of the mesh of standard rain gauge networks, rainfall data commonly available for studies on debris flows often fail to characterise spatially limited cloudbursts which can trigger debris flows in small basins. The instrumentation installed in the Moscardo Torrent basin (rain gauges and sensors which detect debris-flow passage) gives the possibility of analysing the relations between rainstorm characteristics and debris-flow occurrence more precisely than is usually possible in alpine basins.

#### 3.1.2. Ultrasonic sensors

The ultrasonic sensors measure the torrent stage, making it possible to record the debris-flow hydrographs. A logging interval of 60 s was initially (1989) set between two consecutive recordings of the ultrasonic sensors. This logging interval was reduced to 10 s the following year to increase accuracy, and further reduced to 1 s in 1995, thanks to the updating and improvement of the recording system mentioned earlier.

The mean propagation velocity of the front can be calculated in the monitored reach as the ratio of the distance between the sensors to the time interval between the occurrence of the peak of the debris-flow surge in the two recorded hydrographs. The analysis of the hydrographs recorded by the ultrasonic sensors may show the aggradation or degradation of the channel bed at the recording sites. Flow stage measurements and topographic survey of the monitored sections make it possible to estimate peak discharges and total volume of debris flows (Arattano et al., 1997). Debris-flow volumes have been estimated as:

$$\mathrm{Vol} = \int_{t_0}^{t_f} vA(t)\mathrm{d}t = v\int_{t_0}^{t_f} A(t)\mathrm{d}t \qquad (1)$$

where Vol is the volume of flowing mass (water and solid particles); $v$ is the mean flow velocity, which was assumed equal to the mean front velocity; $A(t)$ is the cross-section area occupied by the flow at the time $t$, known from topographic surveys and the ultrasonic data; $t_0$ is the time of arrival of the surge at the gauging site; and $t_f$ is the time at the end of the debris-flow wave. Mean velocity of the main front was used for volume computation because it is the only velocity value available for all recorded events and concerns the part of the debris-flow wave with the highest sediment concentration. This approach to the computation of the flowing volume assumes that the material flows through the considered section at a constant velocity during the surge. Actually, velocity variations occur in debris flows: velocity measurement, carried out using video pictures available for two events that occurred in 1996, has shown that an increase of velocity occurs behind the front and then surface velocity remains higher than front velocity for a significant portion of the debris-flow wave (Arattano and Marchi, 2000). Using mean front velocity could then result in an underestimation of debris-flow volumes. Computed debris-flow volumes should then be regarded as approximate estimates.

*3.1.3. Seismic sensors*

The seismic detectors (seismometers and geophones) record ground vibrations induced by the passage of a debris flow. The first results obtained showed that these detectors are suitable for velocity measurements (Arattano and Moia, 1998). The ground vibration peak is detectable by a seismic sensor placed at a safe distance of some tens of metres from the channel bed. The mean front velocity can then be measured by placing detectors at a known distance from each other along the torrent, adopting the same procedure previously described for velocity measurements with ultrasonic sensors.

The output signal of the seismic sensors is a voltage proportional to the ground oscillation velocity. Then the amplitude is calculated as:

$$\mathrm{Amp} = \frac{\sum_{i=1}^{100} |v_{gi}|}{100} \qquad (2)$$

where Amp is the amplitude, $v_{gi}$ is the ground oscillation velocity and 100 is the number of digital samples in each second of recording.

As mentioned above, the site instrumented with seismic sensors lies about 1 km upstream from the site monitored with ultrasonic gauges. The seismic network, consisting of four pairs of detectors (seismometers and geophones), was set along the bank of a straight channel reach, the length and slope of which are 303 m and 14.9%, respectively.

*3.1.4. Fixed video camera*

A fixed video camera was installed in 1995 on the alluvial fan of the Moscardo Torrent (Fig. 4) to allow a visual interpretation of the debris-flow features. Video recordings were also used for estimating debris-flow surface velocity. The video camera shoots slantwise a straight channel reach about 80 m long and is triggered by the upstream ultrasonic sensor by means of a software that identifies abrupt increases of the stage in the torrent.

## 4. Debris-flow records

Two debris flows that occurred in 1989 are not considered in this study because the logging interval (1 stage value per minute) did not ensure sufficient accuracy. From 1990 to 1998, 15 debris flows occurred; 14 of which were recorded by the installed gauges; for one event (June 23, 1998), only the rainfall and time of occurrence are known. Table 2 indicates the data measured by the installed instrumentation.

Table 2
Recorded data

| Event date | Flow stage (ultrasonic gauges) | Ground vibrations (seismic sensors) | Video recordings | Monitoring sites (Figs. 1 and 4) |
|---|---|---|---|---|
| 17.08.1990 | • | | | 4 |
| 13.08.1991 | • | | | 4 |
| 30.09.1991 | • | | | 4 |
| 01.09.1992 | • | | | 4 |
| 11.07.1993 | • | | | 4 |
| 19.07.1993 | • | | | 4 |
| 20.07.1993 | • | | | 4 |
| 14.09.1993 | • | | | 4 |
| 18.07.1994 | • | | | 4 |
| 05.07.1995 | | • | | 3 |
| 22.06.1996 | • | • | • | 3, 4 |
| 08.07.1996 | • | • | • | 3, 4 |
| 27.06.1997 | • | | | 4 |
| 24.07.1997 | | • | | 4 |

### 4.1. Rainfall

Rainfall recorded in the Moscardo Torrent from 1990 to 1998 was analysed and storm characteristics of two classes, that is, storms causing debris flow (15 cases) and storms which did not cause debris flow (58 cases) were compared (Deganutti et al., 2000). Several storm variables were taken into account, including total storm rainfall, average intensity, maximum 60-min intensity and antecedent precipitation. A statistical analysis showed that only total storm rainfall and maximum 60-min intensity were significantly different between debris-flow storms and storms that did not trigger debris flows. Rainstorm characteristics affecting the triggering of debris flows and shallow landslides are often represented by means of 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 and Ellen, 1985; Wieczorek, 1987; Larsen and Torres-Sánchez, 1998). In Fig. 5, line #2 delimits the lower envelope of storms which caused debris flows in the Moscardo Torrent. 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 (Deganutti et al., 2000). The critical line of debris-flow rainfall defines the duration–intensity combination, which is necessary, but not sufficient, to trigger debris flows in the studied basin. The equation of the threshold line for the Moscardo Torrent (Fig. 5) is:

$$I = 15D^{-0.7} \tag{3}$$

where $I$ represents the rainfall intensity (mm h$^{-1}$) and $D$ the 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 which are lower and higher respectively than those of Ceriani et al. (line #4 in Fig. 5). Lower

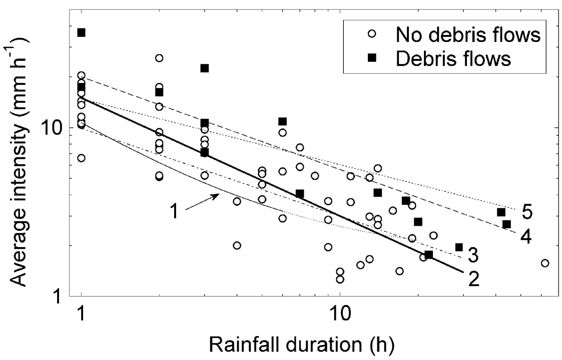


Fig. 5. Relationship between storm duration and average intensity: (1) Wieczorek (1987); (2) Moscardo Torrent (this study); (3) Montgomery et al. (2000); (4) Ceriani et al. (1994); (5) Caine (1980).

rainfall critical intensity in the Moscardo basin can be referred to the fact that, due to critical topographic conditions and physical and mechanical characteristics of debris, comparatively low-intensity rainfall is sufficient to provoke debris flows. Other two critical lines delineating instability thresholds (#1 and #3 in Fig. 5)

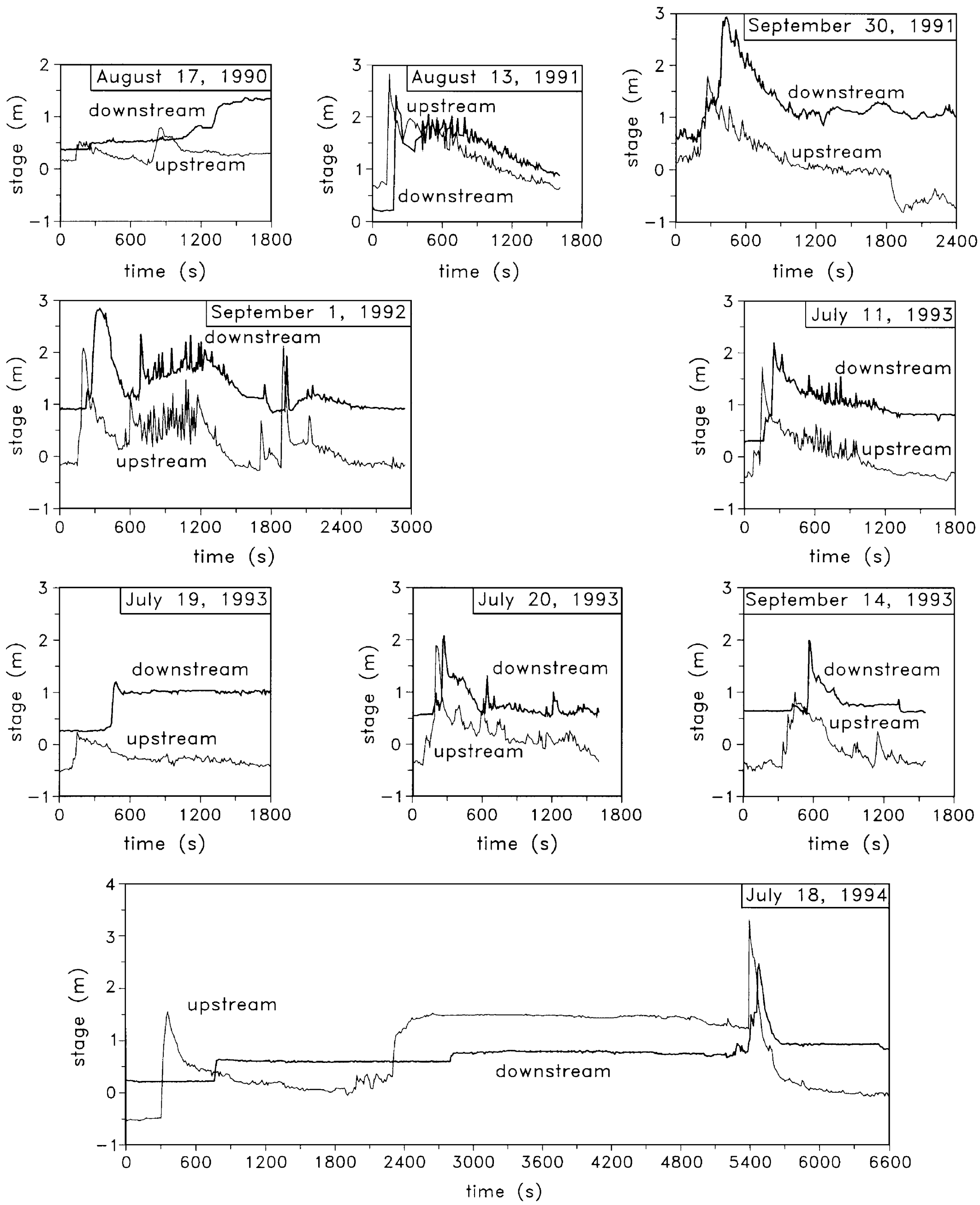


Fig. 6. Hydrographs of debris flows recorded by ultrasonic gauges (1990–1994); the scales for time and stage are the same for all graphs.

are closer to the Moscardo one. 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: rainfall thresholds are less than those developed for abundant or catastrophic debris flows at larger spatial scales. The threshold line obtained by Montgomery et al. (2000) (line #3 in Fig. 5) refers to a recently clear-cut logged basin in coastal Oregon (USA) where high basin disturbance leads to low instability thresholds for shallow landslides and debris flows.

### 4.2. Ultrasonic data

The hydrographs recorded by the ultrasonic sensors for 12 debris flows are shown in Figs. 6 and 7. Mean velocity, peak discharge and volume data are shown in Table 3. The intermediate station sometimes provided irregular recordings for the debris flows of 1996–1997: in these cases, only the average values computed between the upstream and downstream gauges are reported. The hydrographs recorded in the Moscardo Torrent show relevant differences from event to event. In particular, velocities and hydrograph shapes may differ (Table 3 and Figs. 6 and 7). Because of the widening of the channel and the abrupt decrease in slope occurring at the downstream station due to the presence of a ford, the passage of debris flows sometimes causes a deposition of debris-flow material at this station. On August 17, 1990 two small debris-flow surges observed at the upstream station resulted in aggradation of the channel bed at the downstream station. A similar pattern was observed for the first two surges of the July 18, 1994 debris flow, while the third surge washed away the deposits left by the second surge at the upstream station and flowed over the deposits of the previous surges at the downstream station without adding further deposits. Evidence of

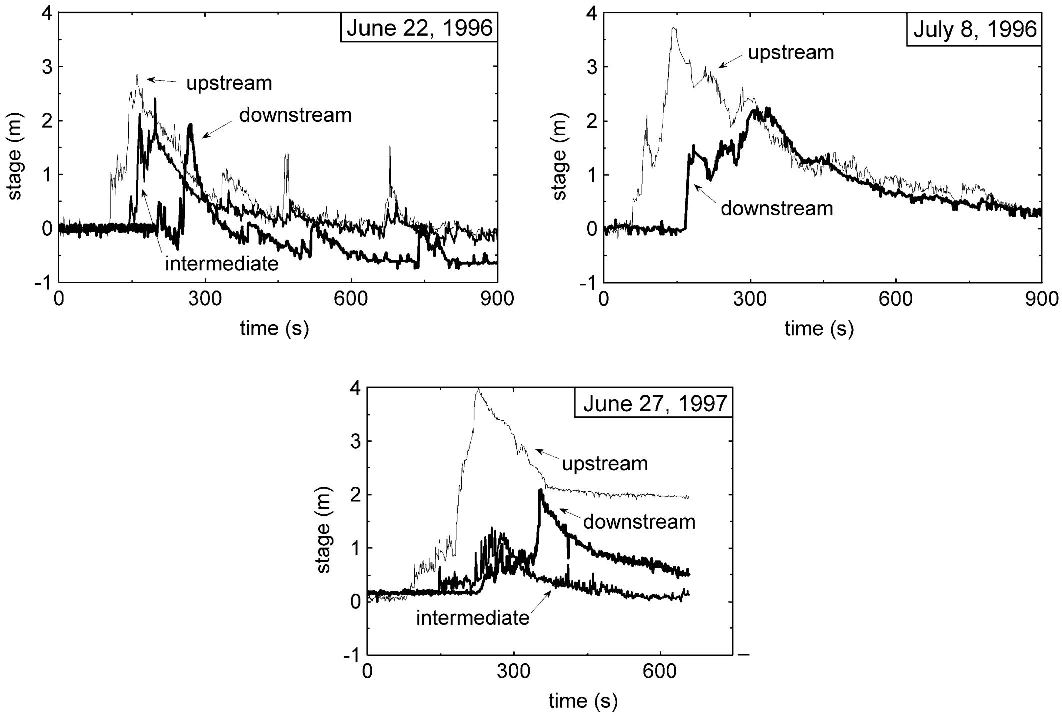


Fig. 7. Hydrographs of debris flows recorded by ultrasonic gauges (1996–1997); the scales for time and stage are the same for all graphs.

Table 3
Velocity, discharge and volume estimated from ultrasonic sensors measurements

1990–1994: Two gauging stations

| Event date | Mean front velocity (m s$^{-1}$) | Peak discharge (m$^3$ s$^{-1}$) | Discharged volume (m$^3$) |
|---|---|---|---|
| 17.08.1990 | 1.0 | – | – |
| 13.08.1991 | 5.0 | 88 | 19,000 |
| 30.09.1991 | 1.9 | 24 | 3250 |
| 01.09.1992 | 2.5 | 46 | 5800 |
| 11.07.1993 | 3.0 | 14 | 5600 |
| 19.07.1993 | 0.9 | 3 | 730 |
| 20.07.1993 | 4.3 | 16 | 6500 |
| 14.09.1993 | 2.5 | 10 | 3800 |
| 18.07.1994 | 4.0 | – | – |

1996–1998: Three gauging stations

| Event date | Gauging station | Mean front velocity (m s$^{-1}$) | Peak discharge (m$^3$ s$^{-1}$) | Discharged volume (m$^3$) |
|---|---|---|---|---|
| 22.06.1996 | upstream | | 132 | 16,800 |
| | | 3.2 | | |
| | middle | | 136 | 15,600 |
| | | 3.8 | | |
| | downstream | | 151 | 16,000 |
| 08.07.1996 | upstream | | 255 | 65,800 |
| | | 4.0 | | |
| | downstream | | 134 | 49,800 |
| 27.06.1997 | upstream | | | |
| | | 2.9 | 25 | 3000 |
| | downstream | | | |

aggradation was also occasionally observed in other measuring sites, for example, at the upstream sensor on June 27, 1997 (Fig. 7).

Sometimes debris flows appear in the Moscardo Torrent as a single, well-defined wave with a steep front followed by a continuous and regular decrease in flow height. A few, well-defined, smaller waves may follow the main surge; in other cases, the recession limb appears to be very irregular with abrupt fluctuations of the stage, as if many smaller waves had followed the main surge. Discharge and volume computations were not carried out for events characterised by channel aggradation or degradation.

### 4.3. Seismic data

Seismic sensor records are presented as graphs of amplitude versus time. The plot for the debris flow of June 22, 1996 (Fig. 8) shows a peak in the initial phase of the event, which corresponds to the passage of the debris-flow front. Some secondary surges are also identifiable in the recession phase of the event. The mean front velocity of the main surge in the instrumented reach varies from 7.1 to 8.5 m s$^{-1}$: these values are higher than those estimated through the ultrasonic gauges on the alluvial fan (Table 3) and may be due to the higher gradient of the channel stretch equipped with seismic detectors. The seismic recordings of the July 8, 1996 debris flow (Fig. 8) can be interpreted as the occurrence of several surges of similar intensity, all of them smaller than the main surge of the June 22, 1996 event. This contrasts with data recorded on the alluvial fan by the ultrasonic gauges, which show a well-defined debris-flow front with flow depth and discharge higher than the June 22 event (Fig. 7). The July 8, 1996 debris flow probably col-

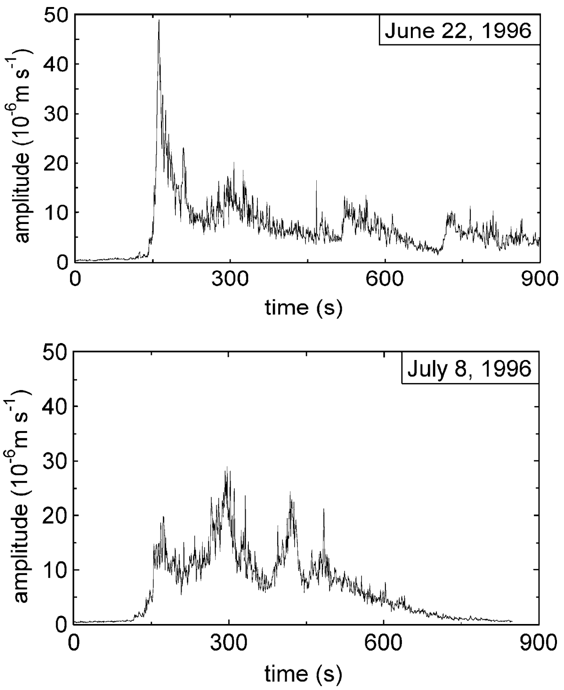


Fig. 8. Debris-flow recording using seismic detectors: plot of ground vibration amplitude versus time (1996 debris flows).

lected further material between the seismic sensor site and the ultrasonic gauge site, increasing in volume particularly in the frontal part (Arattano and Moia, 1998).

The amplitude versus time graph for the July 24, 1997 debris flow, calculated from the recordings of the upstream seismic network (Fig. 4), is shown in Fig. 9a. Even though a first peak can be easily isolated in this graph, its shape shows fluctuations of amplitude comparable, as far as their intensity is concerned, to those associated with the first surge. Fig. 9b shows the amplitude versus time graph from the recordings of the downstream seismic detectors located on the fan (Fig. 4). Here a main wave with a steep front followed by smaller waves is recognisable. This occurrence has led to the assumption that sometimes debris flows may develop a main front only after they have reached the fan (Arattano, 2000).

The mean debris-flow velocity in the channel stretch between the upstream seismic sensor site and the site instrumented on the alluvial fan was also computed. Results were 3.7 m s$^{-1}$ for the June 22, 1996 event, 2.4 m s$^{-1}$ for the July 8, 1996 event and 4.0 m s$^{-1}$ for the July 24, 1997 event. For this latter debris flow, no data from ultrasonic recordings are available and the downstream data derive from seismic sensors installed close to the intermediate ultrasonic gauge (Fig. 4). The value obtained for the June 22, 1996 event is consistent with the decrease in velocity observed from the upstream reach (seismic sensors site) and the downstream reach, equipped with the ultrasonic gauges (Table 3). In the July 8, 1996 debris flow, the low mean velocity between the seismic and ultrasonic sites could be due to the loss of energy caused by the erosion of channel banks or by the removal of the debris produced by small landslides on the banks of the torrent before and during the passage of the debris flow (Arattano and Moia, 1998). Sediment influx from channel slopes might also explain the change in wave shape between the seismic and ultrasonic sites. Another possible explanation could be the complete or partial temporary deposition of the debris-

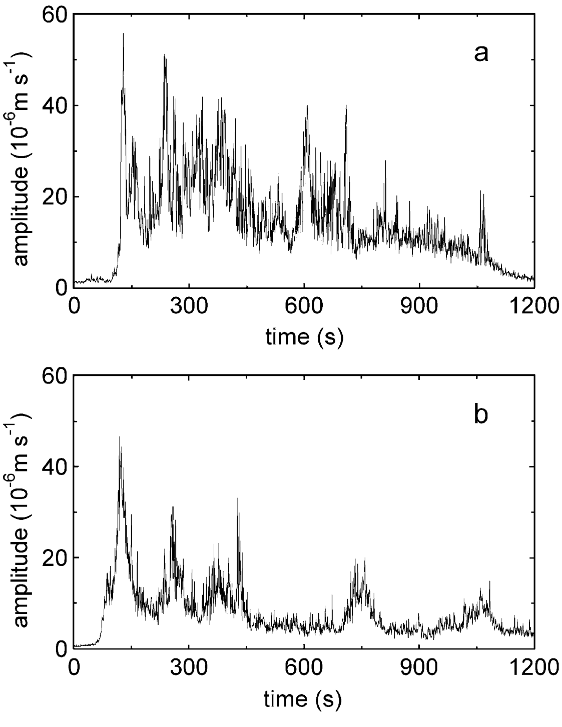


Fig. 9. Debris-flow recording using seismic detectors: plot of ground vibration amplitude versus time (July 24, 1997): (a) seismic sensor at the upstream monitoring site; (b) seismic sensor on the alluvial fan.

flow material which was then remobilised by further surges coming from upstream.

### 4.4. Video recorded images

#### 4.4.1. Video observations

In 1996, two debris flows, occurring on June 22 and July 8, were recorded by the video camera, allowing their accurate description.

The video images show that both events were preceded by a precursory surge, which consisted of a sediment–water mixture, characterised by strong turbulence. This first surge carried many logs and trees in its frontal portion (Fig. 10a); coarse woody debris were supplied by shallow landslides affecting forested slopes along the torrent. About 1 min after this initial surge, the debris-flow peak arrived with a number of large boulders (up to 2–3 m in diameter) in an abundant muddy matrix (Fig. 10b). The largest boulders, which protruded above flow surface and were clearly visible, did not seem to move "as though they were on top of the tread of a tractor" (Johnson, 1970), but by overturning, as they were pushed along the channel by the dense fluid matrix in which they were immersed. The latter flowed at a higher velocity than the boulders, contributing to determine their irregular trajectories with moderately turbulent motion. In the debris-flow front, the rigid plug and the laminar

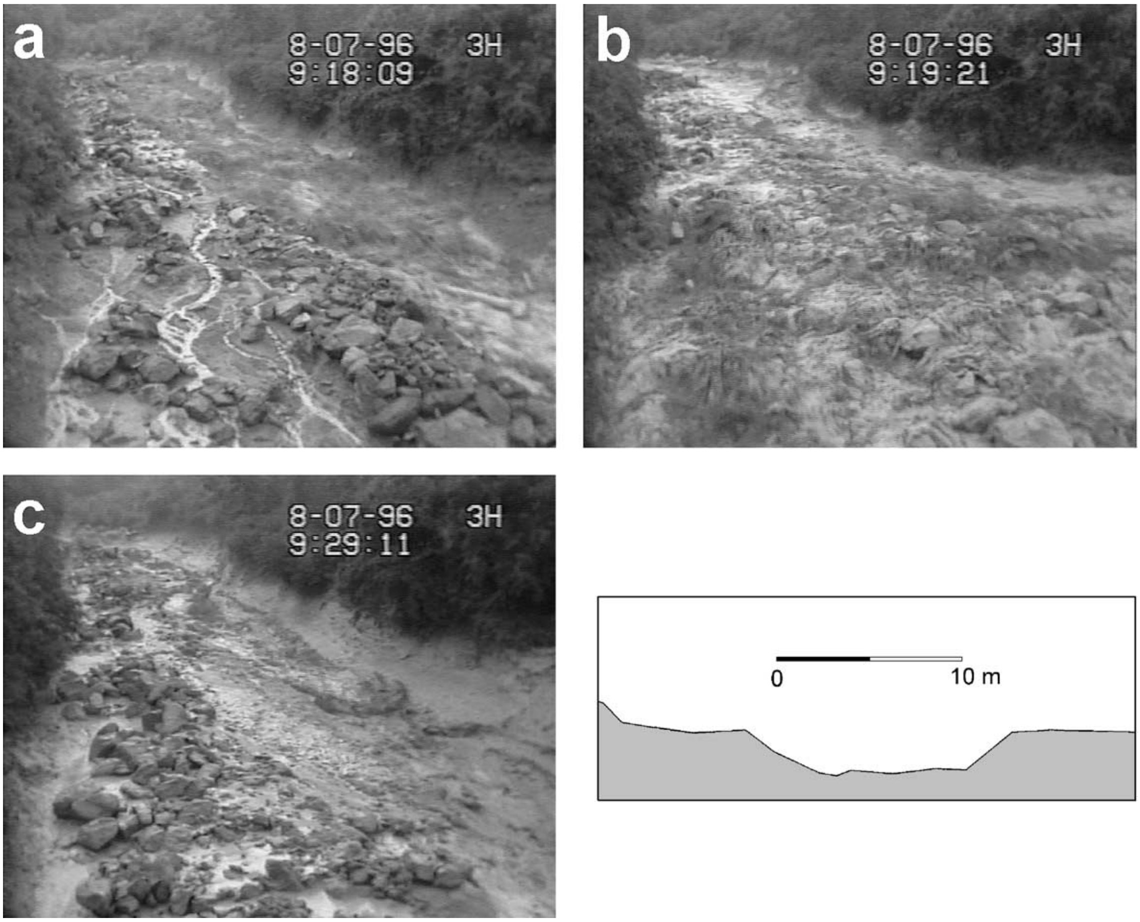


Fig. 10. Selected video pictures of the debris flow of July 8, 1996 and representative cross section: (a) precursory surge; (b) debris-flow peak; (c) secondary wave.

motion often described as typical features of debris flows (Costa, 1984; Johnson and Rodine, 1984; Costa and Williams, 1984) could not be identified. The presence of transverse movement, as regards the direction of the flow, and the possible absence of a rigid plug had already been suggested for previous events to explain how marked boulders, which had been on one bank of the torrent, were found on the opposite bank after the event (Arattano et al., 1997). The videos also show that, behind the front, the presence of boulders became sporadic with a progressive decrease in the concentration of solid particles. This occurred for both events. However, the turbulence of the fluid matrix ceases behind the front to appear again in the last phase of the flow. In both events, a few minutes after the passage of the front peak, further secondary waves of smaller size were observed (Fig. 10c).

### 4.4.2. Surface velocity measurements

As mentioned earlier, in addition to the visual interpretation of debris-flow features, video recordings were used for estimating debris-flow surface velocity. Topographic surveys were carried out after the 1996 debris flows to provide data for the calibration of the camera and of the scene, to be used in processing the recorded images. A simple method, based on the direct computation of the mapping between 2D image points and points in the 3D space, has been developed to perform measurements of surface velocity. This method, described by Arattano and Grattoni (2000), was preferred to a more complex geometric calibration. The developed procedure made it possible to compute 3D space coordinates of selected features and objects from 2D pixel coordinates identified on video pictures. Average velocity of the features floating on the surface was then computed as the ratio of their travelled distance to the time elapsed between the shooting of the video frames that contained them. Average debris-flow velocities estimated through image processing were consistent with measurements based on the recordings of the ultrasonic gauges; velocity variations in debris-flow waves are discussed in Arattano and Marchi (2000).

### 4.5. Field surveys

Geomorphological and topographic field surveys contributed to the interpretation of instrumentally recorded data. The following geomorphological effects of debris flows in fan area can be outlined:

- no avulsions of the channel have occurred;
- debris deposition occurred mainly within the natural banks of the channel, and only some lateral lobes have occasionally been deposited on the fan surface;
- floods characterised by waterlaid processes, occurring between debris-flow events, rework and redistribute debris-flow deposits (Moscariello and Deganutti, 2000);
- the volume of sediment deposited along the instrumented channel stretch significantly varied from event to event, usually being higher for larger events. For instance, abundant deposits were observed along the channel on the alluvial fan after the large debris flow of July 8, 1996. This is also evident in recorded data, which show an evident downstream decrease of discharged volume (Table 3).
- all monitored debris flows reached the main stream, sometimes causing its partial damming.

## 5. Discussion

The video images recorded in 1996 have allowed the analysis of debris-flow characteristics during the different stages of the event: a comment is proposed hereafter.

Even if a rigid plug was not present and moderate turbulence was noticed in the front portion of the flow, the observed phenomena have the general characteristics of a debris flow, although with a concentration probably close to the boundary with hyperconcentrated flow. A debris flow can be defined as a wave composed of a highly concentrated dispersion of poorly sorted sediment (from clay to boulder-sized particles) in water, with a steep front consisting mostly of boulders that can be very large and a tail in which the concentration of solid particles progressively diminishes together with its stage. This definition is here intended to globally describe the natural process with all its macroscopic, essential characteristics. Classifying sediment–water mixtures by use of thresholds in rheological behaviour and in sediment concentration to separate different types of flow (Pierson and Costa, 1987; Costa, 1988; Coussot and Meunier, 1996) requires a term to define the entire process, to identify the “wave of sediment and water” that may occur in a

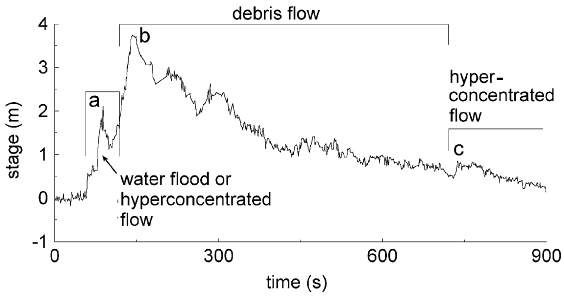


Fig. 11. A single debris-flow wave (Moscardo Torrent, event of July 8, 1996, upstream ultrasonic gauge) can be composed of different types of flow. The approximate extent of debris flow and hyperconcentrated flow in this figure is based on the observation of video images of the event. Letters "a", "b" and "c" correspond to the video frames of Fig. 10.

torrent and that can be clearly identified and isolated in a hydrograph (Fig. 11).

This wave and the entire process have a unity of their own. The term debris flow is in fact often used in literature to mean both the wave and the type of flow with its rheological behaviour and concentration characteristics, which may describe the behaviour only of a portion of the entire debris-flow wave (Fig. 11). The problem could be easily solved, without greatly altering the widely recognised terminology, by adding the term "wave" to the term "debris flow" to distinguish between the entire process and the type of flow. The presence of a steep front causes debris-flow hydrographs to have a typical peaked shape, such as that often described in the literature (e.g. Pierson, 1986; Suwa et al., 1993; Iverson, 1997). But the tail of this wave has generally a lower solid concentration and may be a hyperconcentrated flow or even normal streamflow, as far as the type of flow is concerned (Costa, 1984; Pierson, 1986; Genevois et al., 2000). And in some debris flows, like those in the Moscardo Torrent in 1996, the front is preceded by an evident precursory surge, consisting of a hyperconcentrated flow or normal streamflow (Fig. 11). Thus, a debris flow (meaning the type of flow) always occurs as a part of a debris-flow wave (meaning the global process). Debris flows are always characterised by the presence of a sharp rise in the hydrograph (this is also visible in plots of amplitude versus time, when seismic sensors are employed). Thus, they can be clearly isolated using ultrasonic (or seismic) sensors for the presence of this rise in the graphs (Fig. 11).

The availability of experimental data on flow depth, velocity, peak discharge and volumes in the Moscardo Torrent have allowed a sound comparison with other data sets collected and documented worldwide.

Field data of flow depth and velocity recorded in the Moscardo Torrent are plotted in the graph proposed by Phillips and Davies (1991) (Fig. 12). The velocities measured in the Moscardo Torrent appear to be rather low if compared to the other data in the graph from several debris-flow sites in various countries.

In Fig. 13, data from the Moscardo Torrent are presented in a scatterplot of peak discharge versus debris-flow volume (Rickenmann and Zimmermann, 1993); the references to the data sets presented in the

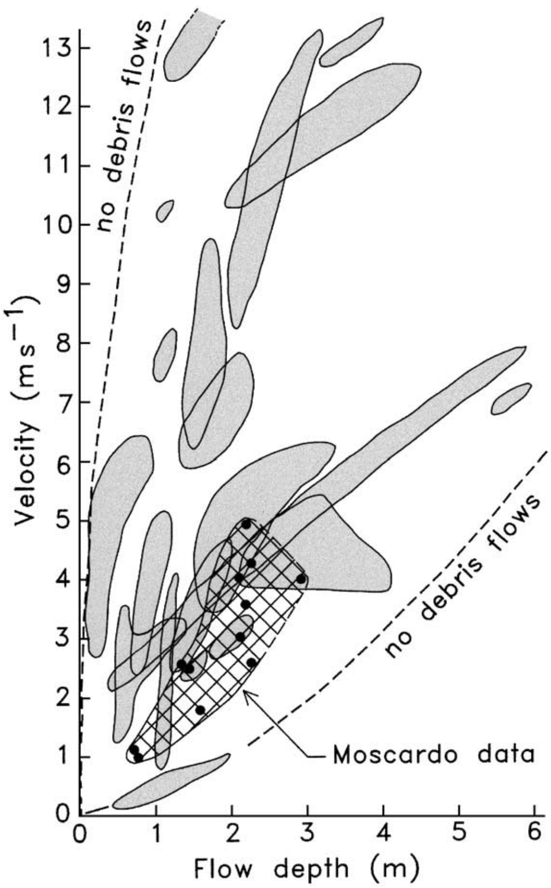


Fig. 12. Plot of depth versus velocity for debris flows: comparison of the Moscardo data with other data sets. Modified from Phillips and Davies (1991).

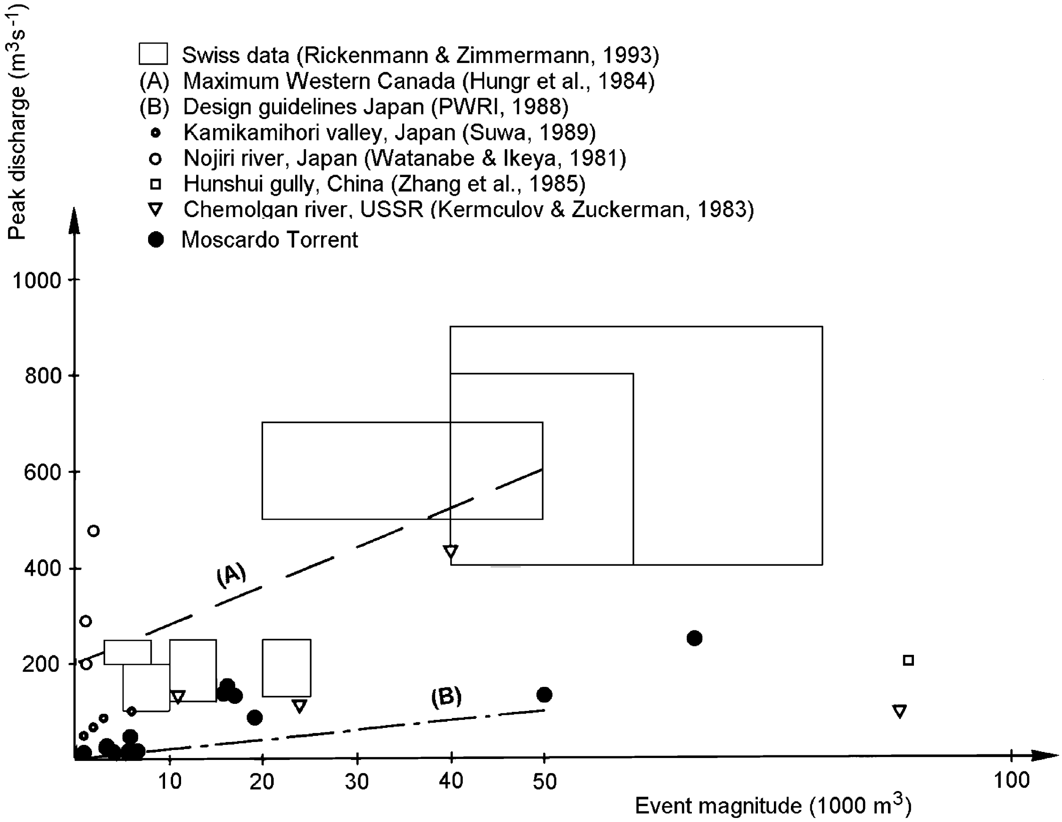


Fig. 13. Relations between debris-flow volumes and discharges (modified from Rickenmann and Zimmermann, 1993).

graph are reported in Rickenmann and Zimmermann (1993). Depending on debris-flow characteristics, a major variability affects discharge values corresponding to the same debris-flow volume. In particular, the highest peak discharges usually pertain to granular debris flows (e.g. Swiss and Canadian data in Fig. 13). Relations between debris-flow volumes and peak discharges are also analysed by Mizuyama et al. (1992) using Japanese data sets: two equations are proposed, for muddy and granular debris flows, respectively, the latter displaying higher values of peak discharge. Rheological and sedimentological investigations (Coussot et al., 1998; Moscariello and Deganutti, 2000) indicate that the Moscardo Torrent produces muddy debris flows; the relation between volumes and discharges shown in Fig. 13 agrees with this classification. Differences in the approaches used for data acquisition increase the variability in the relations between debris-flow volumes and discharge. Some data series derive from instrumented torrents. In other cases, both volume and discharge are obtained from geomorphic measurements after events where debris-flow volumes correspond to topographically surveyed deposits, whereas peak discharges are based on indirect velocity estimations (e.g. superelevation of flow in bends). It should be noted that discharge and volume data from post-event surveys are not homogeneous: field estimates of peak discharge concern the solid–water mixture, whilst topographic surveys of deposits give a measurement of solid volume. Moreover, total volume of a single debris flow often results from several surges. This introduces a further factor of variability in the volume–peak discharge relationships. In spite of these approximations, relations between debris-flow volume and peak discharge can be used to obtain tentative estimates of peak discharges from surveyed or predicted volumes or vice versa (Rickenmann, 1999).

## 6. Conclusions

The Moscardo Torrent data regarding flow depth, velocity, peak discharge and volumes, recorded since 1990, probably represent the largest database of field monitored debris flows currently available in Europe. These data have contributed to widen the data sets on debris-flow characteristics collected worldwide and have been compared with some of these latter. Based on the analysis of the videos of two debris-flow events and their hydrographs, the term "debris-flow wave" has been proposed to define the global process that involves a debris flow, meaning with this latter term the type of flow (Pierson and Costa, 1987).

Even though debris-flow monitoring in the Moscardo Torrent was intended for research purposes, the results have provided suitable indications for the possible use of different gauges in debris-flow alarm systems. In particular, the use of seismic devices in warning systems (LaHusen, 1996), as has been tested for snow avalanches (Leprettre et al., 1996; Decker et al., 1997; Suriñach et al., 2000) appears to be encouraging (Arattano, 1999). Seismic and ultrasonic detectors might be employed in warning systems on transportation routes until structural and more definitive measures can be taken or when structural control works are not economically feasible. It would be less suitable to use these detectors (or other systems that provide an alarm after a debris flow has started) for protecting urban areas, since the speed with which debris flows occur may not allow enough time for evacuation.

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## References

Arattano, M., 1999. On the use of seismic detectors as monitoring and warning systems for debris flows. Natural Hazards 20 (2–3), 197–213.

Arattano, M., 2000. On debris flow front evolution along a torrent. Physics and Chemistry of the Earth: Part B 25 (8), 733–740.

Arattano, M., Grattoni, P., 2000. Using a fixed video camera to measure debris-flow surface velocity. In: Wieczorek, G., Naeser, N. (Eds.), Proceedings, Second International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. A.A. Balkema, Rotterdam, pp. 273–281.

Arattano, M., Marchi, L., 2000. Video-derived velocity distribution along a debris flow surge. Physics and Chemistry of the Earth: Part B 25 (8), 781–784.

Arattano, M., Moia, F., 1998. Monitoring the propagation of a debris flow along a torrent. Hydrological Sciences Journal 44 (5), 811–823.

Arattano, M., Deganutti, A.M., Marchi, L., 1997. Debris flow monitoring activities in an instrumented watershed of the Italian Alps. In: Chen, C. (Ed.), Proceedings, First International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. Water Resources Engineering Division/ ASCE, New York, pp. 506–515.

Blijenberg, H.M., de Graaf, P.J., Hendricks, M.R., de Ruiter, J.F., van Tetering, A.A., 1996. Investigation of infiltration characteristics and debris flow initiation conditions in debris flow source areas using a rainfall simulator. Hydrological Processes 10 (11), 1527–1543.

Bonte, M., 2000. Initiation of debris flows in cohesive glacial deposits. Geographical Research Abstracts 2 on CD-ROM.

Caine, N., 1980. The rainfall intensity–duration control of shallow landslides and debris flows. Geografiska Annaler 62A (1–2), 23–27.

Cannon, S.J., Ellen, S.D., 1985. Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California. California Geology 38 (12), 267–272.

Ceriani, M., Lauzi, S., Padovan, N., 1994. Rainfall thresholds triggering debris flows in the alpine area of Lombardia Region Central Alps—Italy. Man and Mountain '94, First International Congress for the Protection and Development of Mountain Environment. Mantana, Milano, pp. 123–139.

Costa, J.E., 1984. Physical geomorphology of debris flows. In: Costa, J.E., Fleisher, P.J. (Eds.), Developments and Applications of Geomorphology. Springer, Berlin, pp. 268–317.

Costa, J.E., 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 113–122.

Costa, J.E., Williams, G.P., 1984. Debris flow dynamics. U.S. Geological Survey Open File Report 84-606, Videotape, 23 min.

Coussot, Ph., Meunier, M., 1996. Recognition, classification and mechanical description of debris flows. Earth-Science Reviews 40, 209–227.

Coussot, Ph., Laigle, D., Arattano, M., Deganutti, A.M., Marchi, L., 1998. Direct determination of rheological characteristics of debris flow. Journal of Hydraulic Engineering ASCE 124 (8), 865–868.

Decker, R., Jensen, N., Rice, R., 1997. Automated snow avalanche hazard reduction. In: Chen, C. (Ed.), Proceedings, First International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. Water Resources Engineering Division/ASCE, New York, pp. 530–539.

Deganutti, A.M., Marchi, L., Arattano, M., 2000. Rainfall and debris flow occurrence in the Moscardo basin (Italian Alps). In: Wieczorek, G., Naeser, N. (Eds.), Proceedings, Second International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. A.A. Balkema, Rotterdam, pp. 67–72.

De Vita, P., Reichenbach, P., 1998. Rainfall-triggered landslides: a reference list. Environmental Geology 35 (2–3), 219–223.

Genevois, R., Tecca, P.R., Berti, M., Simoni, A., 2000. Debris flow in the Dolomites: experimental data from a monitoring system. In: Wieczorek, G., Naeser, N. (Eds.), Proceedings, Second International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. A.A. Balkema, Rotterdam, pp. 283–291.

Innes, J.L., 1983. Debris-flows. Progress in Physical Geography 7 (4), 469–501.

Itakura, Y., Fujii, N., Sawada, T., 2000. Basic characteristic of ground vibration sensors for detection and mass-estimation of debris flow. Physics and Chemistry of the Earth: Part B 25 (8), 717–720.

Iverson, R.M., 1997. The physics of debris flows. Reviews of Geophysics 35 (3), 245–296.

Johnson, A.M., 1970. Physical Processes in Geology. Freeman, Cooper and Company, San Francisco, 577 pp.

Johnson, A.M., Rodine, J.R., 1984. Debris flow. In: Brunsden, D., Prior, D.B. (Eds.), Slope Instability. Wiley, New York, pp. 257–361.

Johnson, K.A., Sitar, N., 1990. Hydrologic conditions leading to debris-flow initiation. Canadian Geotechnical Journal 27 (6), 789–801.

LaHusen, R.G., 1996. Detecting debris flows using ground vibrations. USGS Fact Sheet 236-96, USGS web site.

Larsen, M.C., Torres-Sánchez, A.J., 1998. The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico. Geomorphology 24 (4), 309–331.

Leprettre, B., Navarre, J., Taillefer, A., 1996. First results from a pre-operational system for automatic detection and recognition of seismic signals associated with avalanches. Journal of Glaciology 42 (141), 352–363.

Marcial, S., Melosantos, A.A., Hadley, K.C., LaHusen, R.G., 1996. Instrumental lahar monitoring at Mount Pinatubo. In: Newhall, C.G., Punongbayan, R.S. (Eds.), Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City, Philippines, pp. 1015–1022.

Mizuyama, T., Kobashi, S., Ou, G., 1992. Prediction of debris flow peak discharge. International Congress Interpraevent, Forschungsgesellschaft für vorbeugende Hochwasserbekämpfung, Klagenfurt (Australia), vol. 4, pp. 99–108.

Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., Dietrich, W.E., 2000. Forest clearing and regional landsliding. Geology 28 (4), 311–314.

Moscariello, A., Deganutti, A.M., 2000. Sedimentary and hydrologic processes of a debris-flow dominated alluvial fan—Moscardo Fan, Italy. In: Wieczorek, G., Naeser, N. (Eds.), Proceedings, Second International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. A.A. Balkema, Rotterdam, pp. 301–310.

Okuda, S., Suwa, H., Okunishi, K., Yokoyama, K., Nakano, M., 1980. Observations on the motion of a debris flow and its geomorphological effects. Zeitschrift für Geomorphologie, N.F., Supplementband 35, 142–163.

Phillips, C.J., Davies, T.R.H., 1991. Determining rheological parameters of debris flow material. Geomorphology 4 (2), 101–110.

Pierson, T.C., 1985. Effects of slurry composition on debris flow dynamics, Rudd Canyon, Utah. In: Bowles, D.S. (Ed.), Delineation of Landslide, Flash Flood, and Debris-Flow Hazard in Utah. Utah Water Research Laboratory, Utah State University, Logan, pp. 132–152, General series UWRL/G-85/03.

Pierson, T.C., 1986. Flow behavior of channelized debris flows, Mount St. Helens, Washington. In: Abrahms, A.D. (Ed.), Hillslope Processes. Allen and Unwin, Boston, pp. 269–296.

Pierson, T.C., Costa, J.E., 1987. A rheologic classification of subaerial sediment–water flows. Geological Society of America, Reviews in Engineering Geology 7, 1–12.

Rickenmann, D., 1999. Empirical relationships for debris flows. Natural Hazards 19, 47–77.

Rickenmann, D., Zimmermann, M., 1993. The 1987 debris flows in Switzerland: documentation and analysis. Geomorphology 8 (2/3), 175–189.

Rickenmann, D., Hürlimann, M., Graf, C., Näf, D., Weber, D., 2001. Murgang-Beobachtungsstationen in der Schweiz. Wasser, Energie, Luft—Eau, Energie, Air 93 (1/2), 1–8.

Spalletta, C., Vai, G.B., Venturini, C., 1979. Il Flysch ercinico nella geologia dei monti Paularo e Dimon (Alpi Carniche). Memorie della Società Geologica Italiana 20, 243–265.

Suriñach, E., Sabot, F., Furdada, G., Vilaplana, J.M., 2000. Study of the seismic signals of artificially released snow avalanches for monitoring purposes. Physics and Chemistry of the Earth: Part B 25 (8), 721–727.

Suwa, H., Okunishi, K., Sakai, M., 1993. Motion, debris size and scale of debris flows in a valley on Mount Yakedake, Japan. In: Hadley, R.F., Mizuyama, T. (Eds.), Sediment Problems: Strategies for Monitoring, Prediction and Control. IAHS Publication, 217, IAHS Press, Wallingford, U.K., pp. 239–248.

Suwa, H., Yamakoshi, T., Sato, K., 2000. Relationship between debris-flow discharge and ground vibration. In: Wieczorek, G.

Naeser, N. (Eds.), Proceedings, Second International Conference on Debris-flow Hazard Mitigation: Mechanics, Prediction, and Assessment. A.A. Balkema, Rotterdam, pp. 311 – 318.

Watanabe, M., Ikeya, H., 1981. Investigation and analysis of volcanic mud flows on Mt. Sakurajima, Japan. Erosion and Sediment Transport Measurement. IAHS Publication 133, 245 – 256.

Wieczorek, G.F., 1987. Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. Geological Society of America, Reviews in Engineering Geology 7, 93 – 104.

Zhang, S., 1993. A comprehensive approach to the observation and prevention of debris flows in China. Natural Hazards 7 (1), 1 – 23.