Debris flows recorded in the Moscardo catchment (Italian Alps) between 1990 and 2019

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Abstract. This paper presents debris-flows data recorded in the Moscardo Torrent (eastern Italian Alps) between 1990 and 2019. In this time interval, 30 debris flows were observed, 26 of them were monitored by sensors installed on the channel, while four were only documented through post-event observations. Monitored data consist of debris-flow hydrographs, measured utilizing ultrasonic sensors, and rainfall. Debris flows in the Moscardo Torrent occur from early June to the end of September, with higher frequency in the first part of summer. The paper presents data on triggering rainfall, flow velocity, peak discharge, and volume for the monitored hydrographs. Simplified triangular hydrographs and dimensionless hydrographs were derived to show the basic features of the debris flows in the Moscardo Torrent (time to peak, surge duration, flow depth) and permitting comparison with other instrumented catchments. The dataset is made available to the public with the following DOI: https://doi.pangaea.de/10.1594/PANGAEA.919707.

1 Introduction

Debris-flow research requires experimental data that are difficult to collect because of the intrinsic characteristics of these processes. Debris flows are locally rare events: although every year they affect several catchments in a given region, their frequency in most channels is usually low (i.e. less than one event per year), and this makes the deployment of instrumentation not convenient in most potentially affected catchments. The short duration of debris flows, moreover, hampers the possibility of direct observations in channels not equipped with permanent and automatic monitoring devices.

Both post-event field observations and monitoring in instrumented channels are suitable to collect debris-flow data, even if with different resolutions and purposes. Post-event observations enable collecting data (e.g. date of occurrence, deposited volume, traveled distance) at multiple sites or even at the regional scale (Macconi et al., 2008), but permits only the indirect

assessment of important flow variables, such as the flow depth and velocity. Monitoring in instrumented channels enables real-time recording of debris-flow data that cannot be gathered through post-event surveys in ungauged channels. Given the above-mentioned constraints resulting from the episodic debris-flow occurrence, a careful choice of the sites for monitoring is

35   mandatory, the high frequency of the debris flows being a fundamental requisite to justify the investment.

Starting from early studies in Japan and China (Okuda et al. 1980; Zhang 1993), many papers presented and analyzed debris-flow data collected in instrumented channels; a recent review (Hürlimann et al., 2019) discusses achievements and open problems in debris-flow monitoring.

As far as we know, the Moscardo Torrent (Marchi et al., 2002) basin was the first catchment equipped with permanent

40   instrumentation for debris-flow monitoring in Europe. The monitoring activities in the Moscardo Torrent began in 1989-1990 and still keep on, although with some gaps due to the construction of control works in the instrumented channel (1998-2001) and the obsolescence of the instrumentation between 2007 and 2010. Debris-flow monitoring in the Moscardo Torrent was started by the National Research Council of Italy – Research Institute for Geo-hydrological Protection and is continuing, since 2010, in collaboration with the University of Udine.

45   This work aims to present a dataset of debris flows recorded in the Moscardo Torrent between 1990 and 2019, which were so far unpublished or available from various sources. The following data are presented: date of debris-flow occurrence, triggering rainfall, debris-flow hydrographs, peak discharge, and volume. These data were selected because they define the fundamental characteristics of debris flows, and were recorded employing instrumentation (rain gauges and ultrasonic sensors for flow stage measurement) installed in the study catchment across the whole duration of the monitoring period. Data recorded

50   by other instruments, namely seismic sensors (Arattano, 1999) and video cameras (Arattano and Marchi, 2000), which are available only for a part of the monitoring period, are not considered here.

2 The Moscardo Torrent basin

The Moscardo Torrent basin (Fig. 1, Table 1) is located in the Carnic Alps, in the eastern sector of the Italian Alps. The climate is temperate with cold winters and abundant precipitation in all seasons; precipitation from November–December to March–

55   April prevailingly occurs as snowfall. Basin slopes are mostly covered by coniferous forest (Norway spruce and silver fir); bare scree and outcropping rocks are present in the upper part of the catchment and along the main channel.

A deep-seated gravitational deformation involves most of the basin, and a large roto-translational landslide occupies the right slope in the middle sector of the catchment (Marcato et al., 2012). The weak rock mass properties and the presence of large amounts of loose debris result in rockfall and shallow landslides that supply large amounts of debris to the channels.

60   In order to stabilize the channel and reduce the downstream transfer of sediment, several check dams have been built along the Moscardo channel in the last 40 years: a recent paper by Cucchiaro et al. (2019b) describes the characteristics and temporal evolution of these works and analyses their performance in controlling the debris flows.

The Moscardo Torrent basin was chosen for debris-flow monitoring mainly for the high frequency of such events, while other favorable factors are the easy accessibility of the lower and middle parts of the basin, and the presence of a stable channel

65   on the alluvial fan. Early instrumentation was installed in 1989-1990, and the monitoring activities are still on course, although the time series has some gaps.

<Figure 1, Table 1>

3 Debris-flow data

Table 2 reports basic data on the debris flows observed in the Moscardo Torrent basin. Four debris flows, which were not

70   recorded because of malfunctioning of the instrumentation (1995, 2009 and 2010) or because the sensors had been removed when artificial dikes were built in the monitored channel (1998), were documented through field surveys.

The flow stage at the Moscardo Torrent is recorded using ultrasonic sensors. The sensors are installed in the middle sector of the alluvial fan, where the channel has an average slope of 10%, suspended on a tension structure over the thalweg. The location of the instrumented cross-sections and the recording intervals varied during the monitoring period (Fig. 1 and Table

75   3). We underline the relatively coarse recording interval (10 s) of the debris flows observed from 1990 to 1994. Until 1997 the channel on the alluvial fan was in natural conditions, except a bed sill aimed at protecting a pipeline. Hydraulic works, intended at preventing the overflowing of the alluvial fan were implemented in 1998-2000: the channel was artificially widened and lined with riprap and bed sills, and dikes were built. Figure 2 compares three cross-sections of the channel under natural conditions, surveyed in 1991-1993 with two lined cross-sections surveyed in 2012-2016; these cross-sections are located in

80   the mid-fan area, near the monitoring sites A and D (Fig. 1 and Table 3). Artificial cross-sections are wider than the natural ones; the deposition of lateral levees within the artificial channel, however, led to the restoration of partially natural-like morphological conditions (Fig. 3).

Several debris flows consisted of more than one surge; in these cases, the data reported in Table 2 are related to the main surge. The mean debris-flow velocity was calculated as the ratio of the distance between two instrumented cross-sections to

85   the time difference between the occurrence of the peak of the debris flow in the two recorded hydrographs. The debris-flow volume was computed by summing up, over the entire duration of the event, the product of mean flow velocity and cross-section area occupied by the flow at each time increment. The assumptions underlying this approach to volume computation, and the possible associated errors are discussed in Marchi et al. (2002) and Arattano et al. (2015). Based on video recorded at the monitoring station, the analysis of the hydrographs, and on the observation of the deposits in the monitored channel reach,

90   a few events were classified as debris floods. Post-event observations revealed that also these events occurred as debris flows upstream of the alluvial fan: sediment deposition, also favored by check dams for the event of 24.08.2006 (Arattano et al., 2012), led to transformation into debris floods. No debris floods were observed in the first year of monitoring: the absence of video observations until 1996 could have caused some debris floods to remain unperceived.

<Table 2, Table 3, Figure 2, Figure 3>

Natural Hazards
and Earth System
Sciences
Discussions

95   The rain gauges installed in the Moscardo basin (Fig. 1) are intended to record the rainfall during the debris-flow season (from late spring to autumn) and are not equipped with heating elements. Table 4 reports their years of operation, elevation, and logging intervals.

<Table 4>

4 Summary of recorded data

100   ### 4.1 Debris-flow occurrence

The debris flows in the Moscardo Torrent occurred in a time interval of 118 days, from the beginning of summer (4 June 2019) to early autumn (30 September 1991), with 18 out of 30 events occurring in the first 50 days (Fig. 4).

Rainfall data were analyzed to explore a possible control of intense rainfall on the seasonal distribution of the debris flows. A study by Deganutti et al. (2000) after the first years of monitoring has shown that debris flows in the Moscardo basin were
105   triggered by rainstorms which had a minimum of 21 mm of total rainfall and at least a 60' rainfall intensity of 12.6 mm h^{-1}. These thresholds identify rainstorms that have the potential of causing debris flows in the Moscardo (potentially triggering rainstorms), but they are often exceeded also by rainstorms that do not cause debris flows. The rainstorms that exceed these two thresholds of total rainfall amount and 60' intensity were computed for the rain gauges of Pramosio (1990-1998), Rio Lares (1998-2006 and 2011-2016), and la Musa (2012-2019). In the first years of observation, the rain gauge of Pramosio
110   shows that most potentially triggering rainstorms occurred in June and July (24 rainstorms, versus 15 in August and September). The most recent period, however, shows a much more balanced distribution of intense rainstorms, both at Rio Lares (27 events in June and July versus 29 in August and September), and at La Musa (13 events in June and July versus 16 in August and September). If we consider the entire observation period (1990-2019), the distribution of potentially triggering rainstorms does not show a disproportionate number of events in the first 50 days, and the occurrence of such storms across
115   the debris-flow season is almost constant (Fig. 4). The absence of a rain-gauge that covers the entire monitoring period prevents more definite conclusions, but the analysis of available rainfall data indicates that the differences in the occurrence of intense rainstorms between June-July and August-September are not closely related to the higher frequency of the debris flows in the first part of summer.

Another possible factor that explains the more frequent occurrence of debris flows in the first part of summer is the larger
120   availability of debris stored in the channel bed in the debris-flow initiation areas after winter and the snowmelt period. Field observations support this interpretation, but the absence of systematic measurements of variations in sediment availability does not permit us to confirm it.

<Figure 4>

Figure 5 shows the days of debris-flow occurrence in the 30 years of observations: the tendency toward the earlier
125   occurrence of debris flows is weak (linear regression coefficient r = - 0.17) and not significant (p-value=0.363).

<Figure 5>

4

Most debris flows (69%) occurred in the second half of the day, with 9 events from 12 to 18 hours and 9 from 18 to 24 hours: this is consistent with the triggering commonly caused by summer convective rainstorms, which mostly take place in the afternoon or the evening. Only three debris flows were observed in the morning (6 to 12 hours). For 4 out of the 30 events,

130 the hour of occurrence is not known: these debris flows were not recorded by the monitoring system and are only known through post-event observations (Table 2).

Figure 6 plots the number of debris flows in each year and the cumulative number of debris flows in the observation period. The lack of debris flows in 2007 and 2008 could be referred to the construction of check dams along the main channel in the middle and lower part of the basin (Cucchiaro et al., 2019b) that trapped most of the material and prevented the debris flows

135 to reach the alluvial fan, but this does not apply to the years 2013-2015. We could argue that the large evacuation of sediment from the catchment in two large debris flows of September 2012 (Table 2) required a few years of sediment recharge before new debris flows were produced. However, the lack of data on the variations of sediment storage in the source areas does not permit us to confirm this interpretation. Similar mechanisms could be advocated to explain the absence of debris flows between 1999 and 2001. Artificial channel widening and the construction of bed sills (Figs. 2 and 3) could have favored the deposition

140 of some minor flow events, but these factors did not prevent the occurrence of debris flows in the following years. The number of potentially triggering rainstorms in the years 1999-2001, 2005, and 2013-2015, when no debris flows were recorded, was compared with that of the years in which debris flows did occur. The years 2007-2010 were not included in the analysis because no rainfall data are available (Table 4). The mean number of potentially triggering rainstorms in the years without debris flows (2.61), weighted by the number of years of observations at each raingauge), is lower than in years with debris flows (4.86).

145 However, large variability exists in the number of potentially triggering rainstorms, both in the years with (standard deviation 2.29) and without (standard deviation 2.33) debris flows. The absence of debris flows in some years in an active catchment like the Moscardo is probably caused by a combination of extrinsic, weather-related factors, i.e. the occurrence of few intense rainstorms, and factors intrinsic to the catchment, i.e. the effect of control works and temporary scarcity of mobilizable debris.

We underline that our record consists of debris flows that reached the alluvial fan and were monitored there by the installed

150 instrumentation, or documented through post-event surveys. Field observations, although not systematic, have provided evidence of other flow events that did not reach the alluvial fan (for instance, on July 20 and August 20, 2001), not even as debris floods, but the record of these small events is not complete.

<Figure 6>

The mean frequency between 1990 and 2019 is 1.0 event per year including three debris floods (Table 2). The frequency

155 is similar or lower than other instrumented basins in the Alps if the monitoring stations at the basin outlet or on the alluvial fan are considered: Réal (France): 1.0 event/year (Hürlimann et al., 2019), Illgraben (Switzerland): 3-5 debris flow every year plus some debris floods (Hürlimann et al., 2019), Gadria (Italy): 1.3 events/year between 2011 and 2017 (Comiti et al., 2014; Coviello et al., 2020).

4.2 Triggering rainfall

160   The critical rainfall intensity threshold for debris flow occurrence, identified by Deganutti et al. (2000) after the first years of observations (1990-1998), is confirmed by the more recent data (Fig. 7). Moreover, it is possible to identify an upper limit, with the same exponent, for the rainstorms that triggered debris flows in the Moscardo Torrent. Both the lower critical threshold and the upper limit were fitted empirically, an operation that we consider acceptable due to the relatively small sample size. The two rainfall thresholds have the form:

165    $$I = a \cdot D^{-0.7} \tag{1}$$

where *a* is 15 for the lower threshold and 50 for the upper limit.

The different rain gauges location during the monitoring period (Fig. 1 and Table 4), and the coarse time resolution in 1990-98 (hourly data), which can lead to underestimating the triggering rainfall (Marra, 2019 – Natural Hazards) had a limited impact on the critical rainfall thresholds, which lie in a rather narrow intensity belt.

170   <Figure 7>

4.3 Debris-flow hydrographs

The analysis of the debris-flow hydrographs permitted to define their basic characteristics, such as maximum flow depth, time to peak, surges duration. These characteristics have been used to derive triangular hydrographs and dimensionless hydrographs that could be employed to define realistic inputs for debris-flow mathematical models. Such hydrographs could also allow

175   comparisons with hydrographs recorded in other instrumented catchments.

The analysis was performed examining individual debris-flow surges: data from 62 surges were collected, i.e. on average approximately two surges per debris-flow event. The maximum flow depth was computed as the difference between the surge's peak and the level before the start of the flow rise. A minimum rise of 0.5 m was adopted for the analysis: this value is a trade-off between the need of considering all relevant flow surges and the requirement of minimizing the risk of including in the

180   analysis minor level fluctuations that are not representative of the debris-flow behavior in the studied channel. Table 5 reports basic statistical data on the time to peak, the duration of the recession, and the maximum flow depth. In six cases, while the rising limb and the debris-flow peak are clearly defined and allowed the calculation of time to peak and maximum flow depth, the duration of the recession phase could not be properly recognized (for instance, because of substantial channel aggradation).

<Table 5>

185   We have devised, based on the data of Table 5, the triangular hydrographs presented in Figure 8 to provide a simplified representation of the debris-flow hydrographs in the downstream reach of the Moscardo Torrent. We used the summary data related to duration and the maximum depth of the debris-flow surges to define three triangular hydrographs related to different levels of event severity:

a) a hydrograph characterized by the median value of the time to peak, flow depth and recession duration;

190   b) a severe event, coupling a short time to peak, high flow depth and long duration (25th percentile for the time to peak and 75th percentile for flow depth and recession duration);

    c) a low-severity event, featuring a relatively long time to peak low flow depth and short recession (75th percentile for the time to peak and 25th percentile for flow depth and recession duration).

The hydrograph "b" features fast arrival of the front, high flow depth, and long duration (hence high peak discharge and

195 volume too): all these characteristics define a challenging debris-flow event. Opposite conditions characterize the low-severity hydrograph "c". The synthetic representation provided by Figure 8 enables us to define, based on a simple statistical analysis of the data collected, the worst scenario expected in the studied channel, as far as the maximum flow depth and the shortest time to peak of debris flows are concerned. In the absence of mathematical modeling that could provide more detailed information, this can be of some use for the planning of mitigation measures.

200   <Figure 8>

A more detailed representation of hydrographs shape was achieved by averaging the recorded hydrographs of the debris-flow surges. This analysis was performed on the debris flows recorded between 2002 and 2019: data for 12 surges for both the upstream and downstream measuring stations were available. The debris flows recorded between 1990 and 1998 were excluded because of coarser time resolution from 1990 to 1994 and variable cross-sectional geometry. Dimensionless hydrographs were

205 generated normalizing the flow depth by its maximum value and the time by the total surge duration. The flow peaks were aligned to preserve the sharp shape that is a distinctive feature of debris-flow hydrographs. Finally, the ordinates were averaged, and mean debris-flow hydrographs were obtained, one for each measuring station (Fig. 9). Since the duration varies from surge to surge, average debris-flow hydrographs were computed only for the interval covered by at least 50% of the hydrographs, which led to consider six hydrographs for both the considered measuring cross-sections. The choice of averaging the

210 hydrographs on the interval covered by at least 50% of the events is intended to limit the impact on the results of the peculiar characteristics of single surges.

<Figure 9>

The dimensionless hydrographs at the two measuring stations, which are quite close to each other (Fig. 1) and have similar cross-sectional geometry display similar shapes (Fig. 9). It can be noted that the precursory surge that precedes the peak is

215 somewhat larger in the upstream monitoring station, whereas the ordinates of the intermediate part of the recession phase are higher in the downstream cross-sections and lower in the last part of the recession limb of the hydrograph. These differences could indicate that flow propagation, even in a short (76 m) channel reach, causes non-negligible changes in hydrographs shape. In our particular case, the hydrograph deformation, due to the downstream propagation of the debris flow wave along the channel reach between the stations, does not lead to a spreading of the hydrograph but its shrinkage. It would be interesting

220 to verify if this behavior, which is in contrast to the hypothesis that debris flows behave as kinematic waves, will be confirmed by further observations in this torrent and will be also observed in other catchments.

5 Conclusions

A 30 years dataset of debris-flows recorded an instrumented basin of the eastern Italian Alps has been presented. During the monitoring period, data collection and analysis has been conditioned by variability in available financial resources, and by the implementation of hydraulic works, which caused temporary disruption of data recording. Further disturbance to the operation of the monitoring system came from the malfunctioning and obsolescence of the sensors (especially the ultrasonic sensors), power outages, and damage caused by wind storms. Notwithstanding these problems, which often affect field monitoring activities, particularly if they are carried on for a long period, the monitoring installations allowed recording 26 out of the 30 debris flows that reached the alluvial fan between 1990 and 2019. For the four remaining events, at least the date of occurrence is known.

The relatively large number of debris-flow hydrographs recorded by the ultrasonic sensors has permitted deriving simplified triangular hydrographs that show the distinctive features of debris flows (short total event duration and a very short time to peak). Based on the values of peak flow depth, time to peak, and total surge duration, three triangular hydrographs were devised that correspond to different event severity. This representation, which could be adopted elsewhere for comparison, provides a quick view of possible debris-flow responses and may help to define realistic inputs to debris-flow propagation models.

A more detailed representation of the shape of the hydrographs was also achieved by averaging the recorded hydrographs of the most representative debris-flow surges and generating dimensionless hydrographs, one for each gauging station, through the normalization of the flow depth by its maximum value and the time by the total surge duration. These dimensionless hydrographs provide a characterization of the shape of the hydrographs at the two measuring stations in the studied channel. This may enable comparison with the monitoring results obtained in other instrumented catchments, allowing to identify similarities and differences and relate them to basin and channel characteristics. Finally, it could also permit the study of the hydrograph deformation along the torrent and provide insights on the dynamical behavior of debris flows.

The Moscardo Torrent dataset could contribute to further analysis, in addition to those already carried out and reported in previous studies and those briefly outlined in this paper. We mention here the comparison of triggering rainfall and basic flow variables (depth, velocity, volumes) with other basins instrumented for debris-flows monitoring under different climate and geolithological conditions (Hürlimann et al., 2019).

Some limitations that arise from data presentation need to be mentioned. Rainfall data have been recorded at various rain gauges located at different elevations within or near the catchment: it is thus not available a time series of precipitation recorded at the same rain gauge for the whole monitoring period. Changes in the channel topography caused by hydraulic works, as well as and the rather low recording interval of the hydrographs until 1994, limit the use of numerical models for the reanalysis of the debris flows recorded in the first years of monitoring. Another problem is that debris-flow monitoring was not fully matched by systematic topographic surveys that permit assessing the variation of sediment stored along the channels and the amounts of erodible debris in the source areas connected to the channel network. Beginning in 2011 (Blasone et al., 2014),

Natural Hazards
and Earth System
Sciences
Discussions
EGU
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255 Terrestrial Laser Scanner (TLS) and Structure from Motion (SfM) topographic surveys carried out in selected sectors of the basin, have permitted evaluating the erosion and depositions related to debris flows (Cucchiaro et al., 2018) and the effect of check dams on sediment dynamics (Cucchiaro et al., 2019a). The lack of this information for the whole basin and the entire monitoring period, however, hampers the understanding of the variations in frequency and magnitude of the debris flows in the Moscardo Torrent basin.

260

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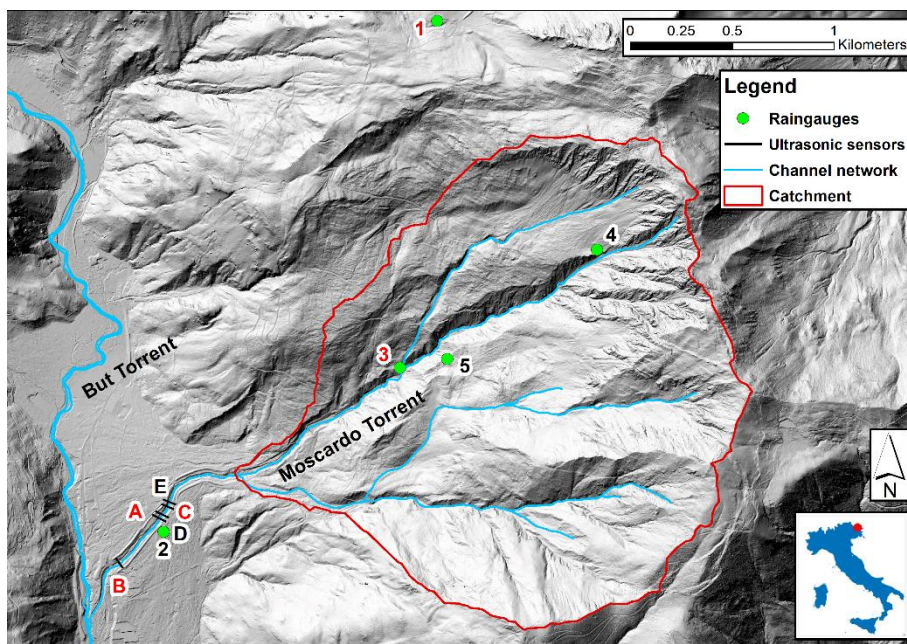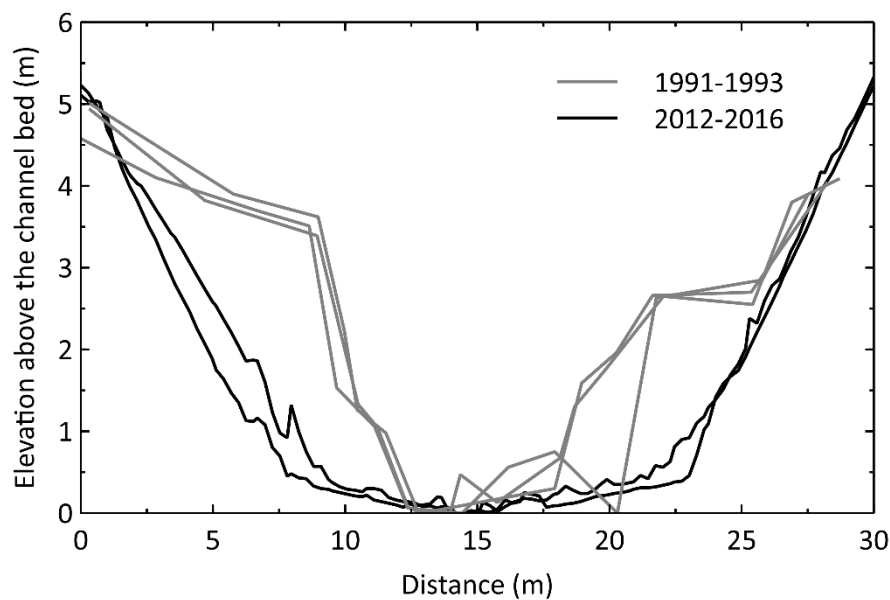   1993.

Figures and tables

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Figure 1. The Moscardo Torrent basin (DTM of Friuli Venezia Giulia Region). The letters and numbers in red refer to monitoring sites that are no more active.

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Figure 2. Cross-sections in the mid-fan area before and after the implementation of control works in 1998-2000.

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Figure 3. Lateral debris-flow levees in the lined channel (a: picture taken on 23 Feb. 2010) and fresh deposits (b: picture taken on 10 June 2019).
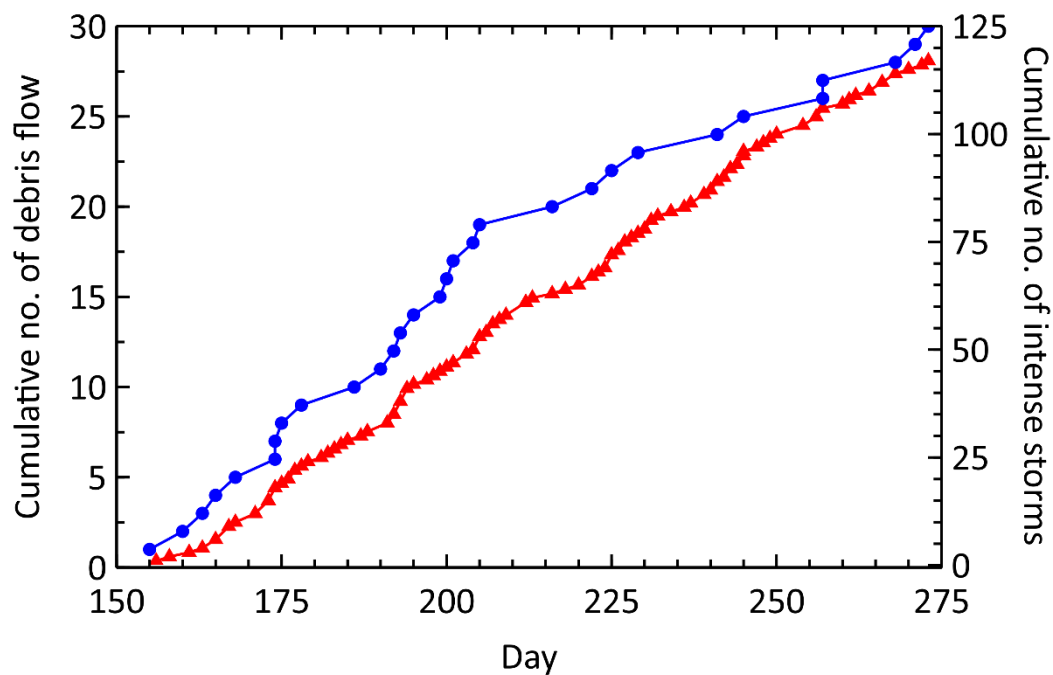

Figure 4. Day of occurrence versus cumulative number of debris flows and intense (potentially triggering) rainstorms in the observation period.
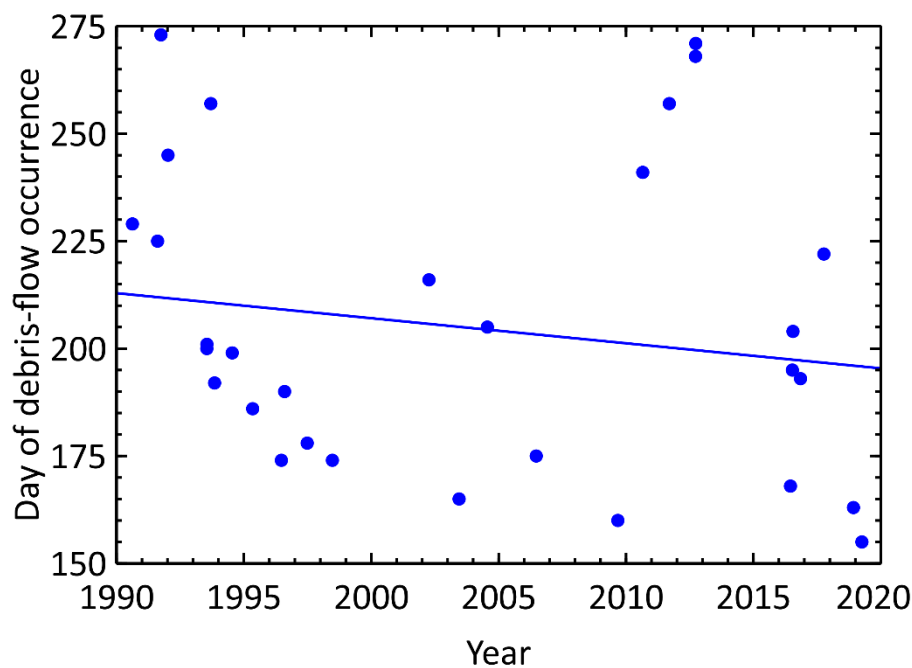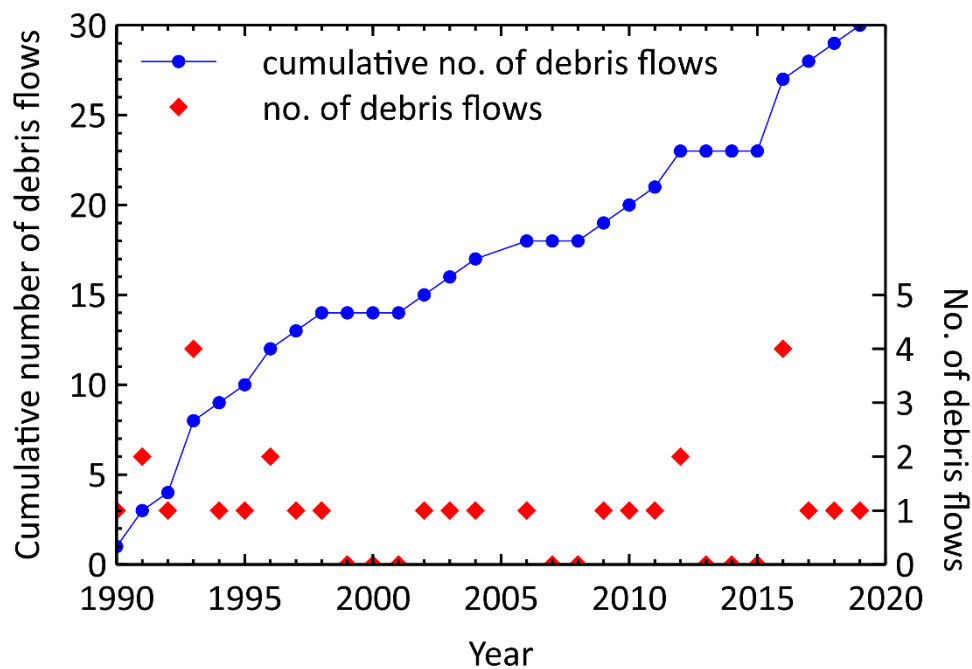
Figure 5. Days of debris-flow occurrence between 1990 and 2019.

350   **Figure 6. Number of debris flows occurred in each year and cumulative number of events in the observation period.**
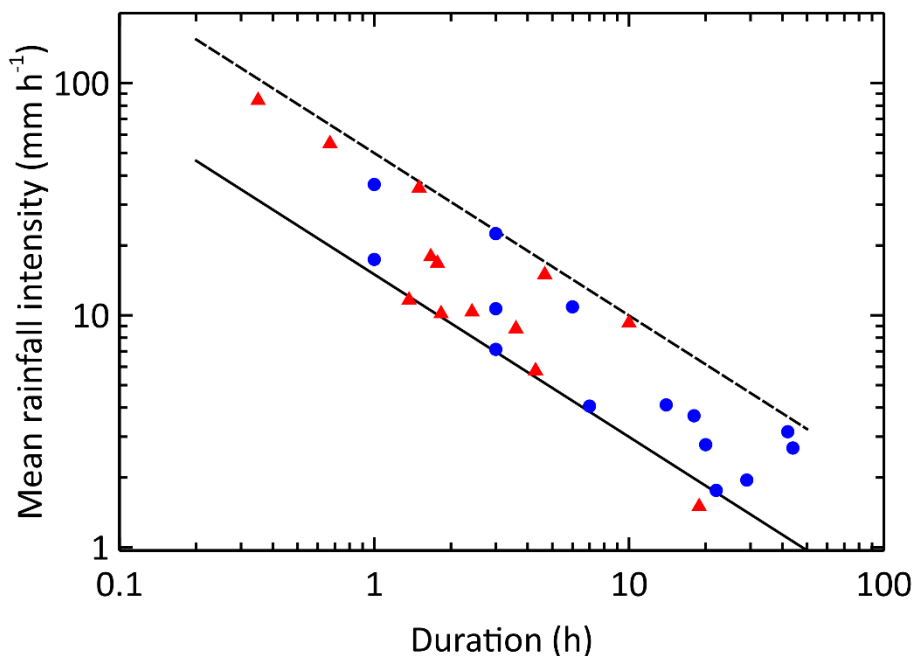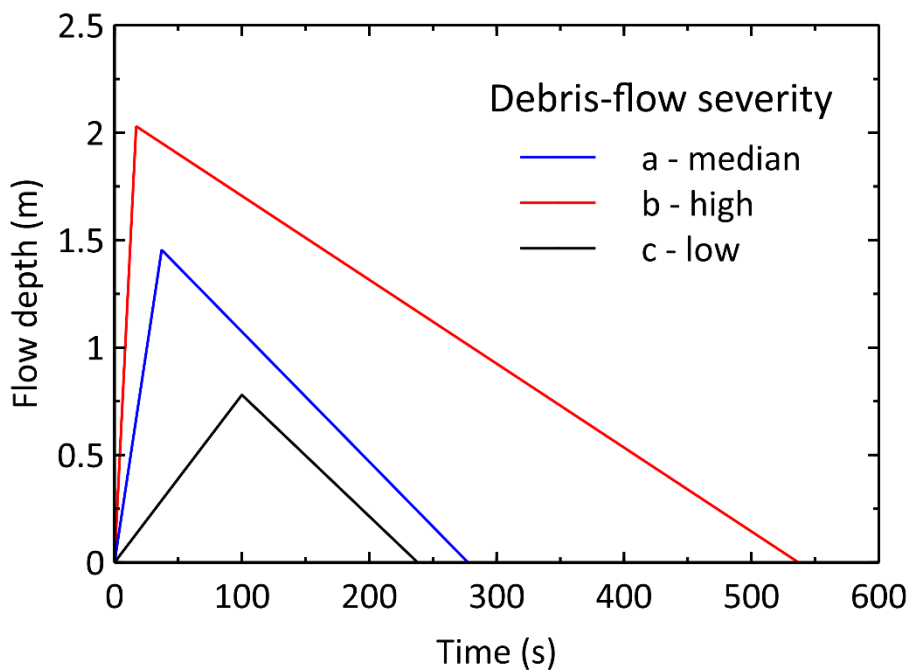
14

Figure 7. Plot of mean rainfall intensity versus duration for debris-flow triggering rainstorms.

355   Figure 8. Simplified triangular debris-flow hydrographs derived from debris-flow surges recorded from 1990 to 2019.

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Figure 9. Dimensionless debris-flow hydrographs (2002-2019).

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Table 1. Basic characteristics of the Moscardo basin.

Basin area (km^2)	4.1
Range in elevation (max elevation – fan apex) (m)	2043 - 890
Mean basin slope (%)	63
Mean channel slope (%)	37
Geology	Carboniferous Flysch (Venturini, 2002)
Mean annual precipitation (mm)	1820 (rain gauge 1 (Fig. 1), years 2010-2019)

365 **Table 2. Debris-flow data; the mean velocity refers to the main surge.**

No.	Event data	Mean velocity (m s^{-1})	Peak discharge (m^3 s^{-1})	Debris-flow volume (m^3)	Previous studies
1	17.08.1990	1.0	-	-	Marchi et al. (2002)
2	13.08.1991	5.0	88	19000	Marchi et al. (2002)
3	30.09.1991	1.9	24	3250	Marchi et al. (2002)
4	01.09.1992	2.5	46	5800	Marchi et al. (2002)
5	11.07.1993	3.0	14	5600	Marchi et al. (2002)
6	19.07.1993	0.9	3	730	Marchi et al. (2002)
7	20.07.1993	4.3	16	6500	Marchi et al. (2002)
*8	14.09.1993	2.5	-	3800	Marchi et al. (2002)
9	18.07.1994	4.0	-	-	Marchi et al. (2002)
10 *	05.07.1995	-	-	-	Marchi et al. (2002)
11	22.06.1996	3.5	139	16133	Marchi et al. (2002)
12	08.07.1996	4	194	57800	Marchi et al. (2002)
13	27.06.1997	2.9	25	3000	Marchi et al. (2002)
14 *	23.06.1998	-	-	51000	-
15	04.08.2002	-	-		-
16 **	14.06.2003				-
17 ***	23.07.2004	5.4	-		Arattano and Marchi (2005)
18 **	24.06.2006	1.6	-	5500	Arattano et al. (2012)
19 *	09.06.2009	-	-		-
20 *	29.08.2010	-	-		-
21	14.09.2011	3.6	71	4700 [a]	Blasone et al. (2014)
22	24.09.2012	3-4 [b]	91-121 [b]	57000 [b]	Blasone et al. (2014)
23	27.09.2012	3-4 [b]	119-159 [b]	89500 [b]	Blasone et al. (2014)
24	16.06.2016	4.5	53-87	15936	Cucchiaro et al. (2019a)
25	11.07.2016	0.5	2-3	-	Cucchiaro et al. (2019a)
26 **	13.07.2016	2.4	22	-	Cucchiaro et al. (2019a)
27	22.07.2016	4.8	95-130	21800	Cucchiaro et al. (2019a)
28	10.08.2017	4.0	61-94	30000	Cucchiaro et al. (2019a)
29	12.06.2018	2.0	-	-	-
30	04.06.2019	0.31	-	-	-

* No monitoring data, only post-event surveys

** Debris flood

*** See Arattano and Marchi (2005) for the velocity computed using cross-correlation

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Table 3. Basic characteristics of the debris-flow monitoring system; the letters in the second column refer to the instrumented cross-sections shown in Figure 1.

Years	No. of ultrasonic sensors	Length of the instrumented channel reach (m)	Recording interval (s)	No. of recorded debris flows
1990-1994	2 (A-B)	300	10	9
1996-1997	3 (C-D, D-B)	370	1	3
2001-2006	2 (E-D)	76	1	4
2011-2012	2 (E-D)	76	2	3
2013-2019	2 (E-D)	76	1	7

Table 4. Rain gauges in the Moscado basin: years of operation and recording intervals. Rain gauges numbers refer to the map of
375 **Figure 1.**

Rain gauge (years of operation)	Code (Fig. 1)	Elevation (m)	1 hour	10 minutes	2 minutes	1 minute	Event recording
Pramosio (1990-1998)	1	1522	●				
Rio Lares (1998-2000)	2	1081			●		
Rio Lares (2001-2006; 2011-2012)	2	1081		●			
Rio Lares (2013-2016)	2	1081					●
Shelter (2013-2019)	3	839				●	
La Musa (2012-2019)	4	1560					●
Pian de Aip (2017-2019)	5	1194					●

Table 5. Basic statistics on debris-flow surges duration and flow depth.

	Valid N	Mean	Std. Dev.	Median	Lower quartile	Upper quartile
Time to peak (s)	62	68	76	44	17	100
Recession duration (s)	56	397	412	234	138	520
Max flow depth (m)	62	1.48	0.76	1.46	0.78	2.03