Monitoring debris flows in the Gadria catchment (eastern Italian Alps): data and insights acquired from 2018 to 2020

Lorenzo Marchi[1], *Velio* Coviello[1], *Marco* Cavalli[1], *Francesco* Comiti[2], *Stefano* Crema[1], and *Pierpaolo* Macconi[3]

[1]CNR-IRPI National Research Council, Research Institute for Geo-Hydrological Protection, corso Stati Uniti, 4 , 35127, Padova, Italy
[2]Free University of Bozen-Bolzano, Faculty of Science and Technology, piazza Università 5, 39100 Bolzano, Italy
[3]Civil Protection Agency, Autonomous Province of Bozen-Bolzano, via Cesare Battisti 23, 39100 Bolzano, Italy

Abstract. This work analyses seven debris flows recorded between 2018 and 2020 in the Gadria instrumented catchment (South Tirol). We focus on three aspects not previously explored in this catchment: (i) the debris-flow transfer times between the headwaters and the outlet; (ii) the longitudinal variability of debris-flow velocity between the three downstream monitored cross-sections, and (iii) the characteristics of the secondary surges observed in three debris flows. In most cases, the mean velocity of the debris flow estimated from the upper to the lower channel reaches (for travel distance of 2155 m) is rather low, ranging between 1.9 and 3.9 m/s. This result could indicate a progressive slowing down, and possibly even temporary stops of debris flows along the path. Some variability in flow velocity was observed between two channel reaches in the lower part of the catchment (0.7 – 2.3 m/s in the upstream reach, and 1.4 – 4.7 in the downstream one). Regarding the secondary surges, these have been noted to occur superimposed on slow-moving slurry-type phases. The mean velocity of the secondary surges varied between 3.5 and 8.9 m/s, with an average value close to 6 m/s for all three events. Their regular shape, duration, and depth suggest that such surges were generated by flow instabilities, with no external forcing.

1 Introduction

Debris-flow monitoring stations provide invaluable data - gained through remarkable resource investments - on such hazardous processes. Pioneering experiences in debris-flow monitoring in China and Japan date back to the 1960s-1970s [1-2]. In Europe, the first permanent installation was the Moscardo Torrent in NE Italy [3]; in the last two decades, several additional sites were instrumented for debris-flow monitoring [cf. 4 for a review]. Among these instrumented catchments, the Gadria Creek, equipped and managed by the Civil Protection Agency of South Tirol, is now acting as a hub for field research on debris flows in the Eastern Alps involving different institutions from Italy and Austria [5-6].

This contribution presents and discusses data on debris flows recorded between 2018 and 2020 (7 events, no debris flows occurred in 2021) in the Gadria catchment, with a specific focus on: i) the occurrence and phenomenology of debris flows in different sectors of the channel (and related flow velocities); and ii) the secondary waves observed in three debris flows recorded in 2020.

2 Study catchment and instrumentation

The Gadria catchment (Fig. 1) drains an area of 6.3 km^2 with a range in elevation between 1,394 and 2,945 m a.s.l.; its lithology consists of metamorphic rocks (paragneiss and orthogneiss); the climate is alpine with mean annual precipitation around 800 mm. Additional information can be found in previous works [7-8].

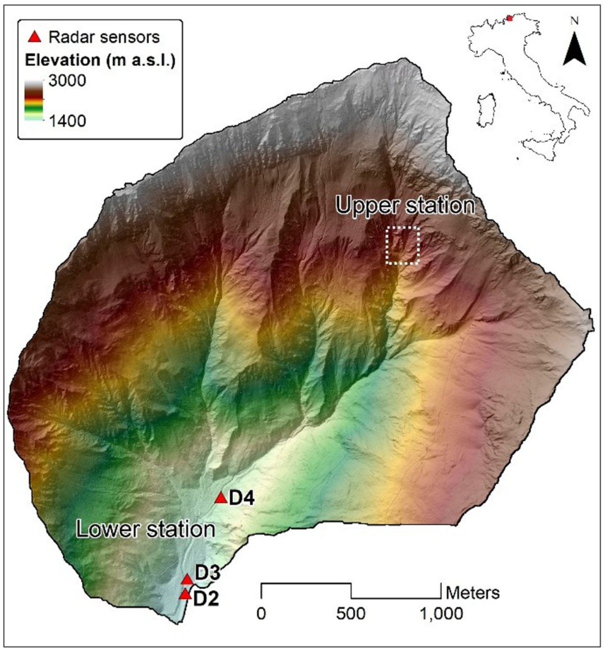

Fig. 1. Map of the Gadria catchment and details of the instruments installed at the lower monitoring station.

This work analyzes the debris-flow hydrographs recorded by three radar sensors (D2, D3, and D4) installed at the lower station. D2 and D3 are located 80 m away from each other with a mean channel slope of 16%, while D4 is installed 549 m upstream of D3. The mean slope between D4 and D3 is 15.6%. The upper station, which was set up in 2018, is located approximately 500 m downstream of the debris-flow initiation area and 2155 m upstream of D4 (mean channel slope is 32%), and is equipped with seismic sensors and a videocamera [9].

3 Results

3.1 Debris flows at the upper and lower stations

During the 7 events recorded between 2018 and 2020 in the lower part of the catchment (stations D2-D4), significant surface runoff and sediment transport (also featuring immature debris flows) were observed at the upper station, just downslope of the initiation areas.

The travel time between the upper and the lower stations was computed as the time difference between the onset of intense runoff with intense sediment transport at the upper station and the first rise of the debris-flow hydrograph at the D4 section. The mean velocity of debris flows between the upper and lower stations was computed as the ratio between the travel time and the distance between the two stations. For most of debris flows analysed here, the resulting values (Table 1) are rather low, especially considering the steep channel slope. We believe that such low mean travel velocities may stem from important variations in flow velocity taking place along the path, including temporary stops of the flowing mass, probably associated to erosion-deposition processes and abrupt changes in channel section geometry. However, actual data to substantiate our hypothesis are not available. Remarkably different from the other events is the 12 August 2020 debris flow. For this event, the large flow depth of the sharp debris-flow front (see Fig. 5a in section 3 of this work), as well as the high flow velocity observed at the lower station (Table 2), are consistent with the short travel time between the upper and the lower stations. In this case, the debris flow was likely not affected by temporary stops or significant slowing down along the path.

Table 1. Travel times and mean flow velocity of the debris flows between the upper station and D4.

Date	Travel time (hh:mm:ss)	Mean velocity (m/s)
21 Jul 2018	00:09:22	3.8
10 Jun 2019	00:09:35	3.7
11 Jun 2019	00:07:37	4.7
26 Jul 2019	00:11:12	3.2
2 Aug 2020	00:16:06	2.2
10 Aug 2020	00:07:51	4.6
12 Aug 2020	00:02:40	13.5

3.2 Debris flows at the lower station

Table 2 presents the mean velocity of debris-flow fronts in the two channel reaches of the lower station. While the two events recorded in 2019 featured similar velocity in the two channel reaches, the other debris flows had higher velocity in the reach D3-D2 than in the upstream reach D4-D3. Although the two channel reaches have similar mean slope, the middle sector of the reach D4-D3 is characterised by wider sections (Fig. 2) and a lower channel slope, in correspondence to the confluence with two tributaries. These features could explain the lower velocity observed in the D4-D3 channel reach.

Table 2. Mean flow velocity, peak discharge, and total volume of debris flows main surges at the lower station. For the 21 July 2018 debris flow, the flow stage measurement at D3 is disturbed and does not allow a reliable computation of peak discharge and volume.

Date	Velocity D4-D3 (m/s)	Velocity D3-D2 (m/s)	Peak discharge (m^3/s)	Volume (m^3)
21 Jul 2018	1.5	5.3	-	-
11 Jun 2019	2.1	2.4	25	7,750
26 Jul 2019	1.3	1.4	16	6,700
2 Aug 2020	0.7	1.7	16	9,700
10 Aug 2020	1.3	3.0	31	15,350
12 Aug 2020	2.3	4.7	108	16,700

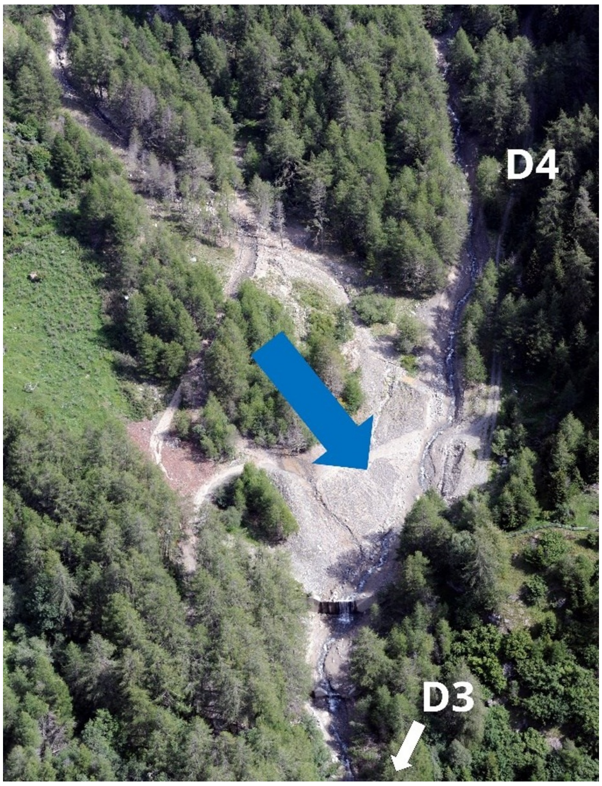

Fig. 2. Aerial photo of the channel between D4 and D3; the blue arrow indicates a low-slope, partly unconfined sector of the channel.

Table 2 also presents the peak discharge and the debris-flow volume calculated, respectively, as the maximum and integral of the product of the mean flow velocity of the main surges in the reach D3-D2 by the flow cross-sectional area. The cross-sectional area was estimated using the flow stage measured at station D3 and assuming the cross-section to be clean from any deposit.

A significant uncertainty in the volume estimation – up to 50% – is possible due to the variability of both flow velocity and cross sectional area during the debris flow [8]. However, calculated values are representative of the main features (e.g., duration, flow height) of the analysed debris flows and are consistent with both field estimations and the sediment yield calculated at the catchment scale using topographic techniques.

The velocity of the June 10, 2019 debris flow could not be reliably estimated in the monitored channel reaches D4-D3 and D3-D2. As shown in Fig. 3, the first part of the hydrograph recorded at D4 shows the typical features of debris flows, with a sudden and fast-rising limb, followed by the peak. This permitted computing the travel time and mean flow velocity between the upper station and D4 (Table 1). However, after the peak, the stage values become almost stable, with values approximately 1.5 m higher than the initial value of the channel bed. The flow levels recorded at D3 and D2 are low and do not permit recognizing a well-defined debris-flow (or flood) wave. A possible interpretation - no video recordings are available for this event - is that the debris flow deposited right downstream of D4 (and affecting its stage measurements after the peak) and only a small, fluid flow reached the downstream sensors D3 and D2.

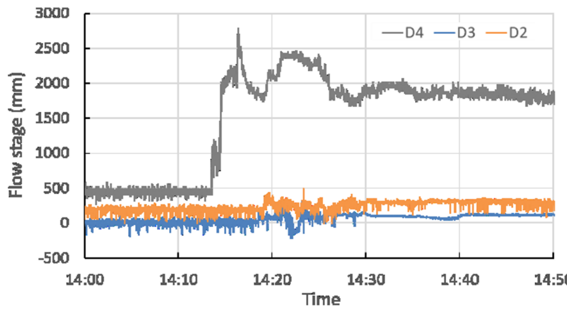

Fig. 3. Hydrographs of the June 10, 2019 event recorded at the lower station.

3.3 Secondary surges

Fast-traveling surges are common features in debris flows [10-11] but, as observed by Huebl et al. [12], field data on their development, shape and velocity are seldom available.

While small, isolate secondary surges are often observed in the recession phase of debris flows in the Gadria Creek, the three events observed on 2, 10 and 12 August 2020 display long (5-15 minutes) and regular sequences of secondary waves at the lower station (Fig. 4). Fig. 5 shows secondary waves recorded at the three monitored cross-sections of the lower station during the 12 August 2020 debris flow. At D3 and D2 (Fig. 5b) the duration of the secondary surges varies from 10 to 20 s, with an average flow depth between 0.6 and 0.8 m.

Table 3 reports the mean values and the standard deviations of flow velocity relative to the secondary surges observed during the August 2020 events. The surge velocity was computed as the ratio between their travel time (i.e., time difference between the peak in stage values at the radar sensors D3 and D2) and the distance between these two cross-sections. An average velocity close to 6 m/s was observed for all three events, and velocities of the individual surges varied between 3.5 and 8.9 m/s. Therefore, the secondary waves display similar kinematic characteristics which are unrelated to the debris-flow front velocity of their "parental" event reported in Table 2.

Table 3. Mean velocity between D3 and D2 for the secondary surges observed in August 2020. Std. dev. is reported in parenthesis.

Date	No. of surges	Velocity (m/s)
2 Aug 2020	17	6.0 (1.2)
10 Aug 2020	18	6.9 (0.7)
12 Aug 2020	31	6.4 (0.9)

A common feature of the August 2020 debris-flow events is a phase of slow-moving slurry on which secondary surges are superimposed, travelling at a much higher velocity. Together with their regular shape, duration, and depth, the presence of slurry in the channel (with a thickness of 0.3-0.8 m) suggests that the surges were generated by intrinsic flow instabilities, without external forcing (e.g., dam-break occurrence upstream).

Fig. 4. Two secondary surges of the August 10, 2020 debris flow.

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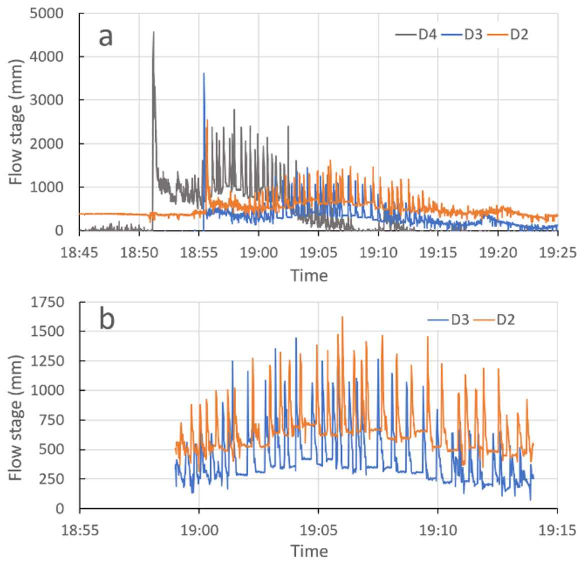

Fig. 5. Debris-flow hydrograph of August 12, 2020 (a) and sequence of secondary waves monitored at the sensors D3 and D2 for the same event (b).

4 Concluding remarks

Debris-flow monitoring in other catchments [e.g. 12-13] has shown the importance of experimental observations in different sectors of the channel: we expect that extending monitoring to the upper part of the Gadria channel could provide useful insights on debris-flow formation and evolution. Previous published studies in the Gadria catchment [7-8] focused on data collected close to the catchment outlet, but since 2018 it has been possible to extend the observations further upstream, up to the headwaters, enabling a more complete monitoring of debris-flow propagation.

Rather low mean velocities were observed between the upper and the lower stations for most of the events occurred from 2018 to 2020, probably due to local deceleration and temporary halting of debris flows.

Some important differences in mean flow velocity were observed also in the short debris-flow channel monitored at the lower station. In fact, velocities in the channel reach D4-D3 were usually lower than in the D3-D2 reach, most likely for the local channel widening and slope reduction in the former reach which favored deceleration - and partial deposition - of debris flows.

Finally, three debris flows that occurred in August 2020 were characterized by sequences of very regular, fast-traveling secondary surges superimposed on a slow-moving slurry. The origin of such surges – whose kinematics were not related to debris flow front velocities – seem to be associated to flow instabilities generated well upstream in the channel network. However, more events – monitored from the headwaters to the outlet - featuring secondary waves are needed to formulate a robust hypothesis on their genesis.

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References

1. P. Cui, X. Chen, Y. Wang, K. Hu, Y. Li, *Jiangjia Ravine debris flows in south-western China*, in Debris-flow hazards and related phenomena Springer, Berlin, Heidelberg, p. 565-594 (2005)
2. H. Suwa, K. Okano, T. Kanno, Ital. J. Eng. Geol. Environ., special issue 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, 605–613 (2011)
3. L. Marchi, F. Cazorzi, M. Arattano, S. Cucchiaro, M. Cavalli, S. Crema, S., Nat. Hazards Earth Syst. Sci., **21**, 87–97 (2021)
4. M. Hürlimann, V. Coviello, C. Bel, X. Guo, M. Berti, M., C. Graf, J. Hübl, S. Miyata, J.B. Smith, H.-Y. Yin, Earth-Sci. Rev., **199**, 102981 (2019)
5. V. Coviello, M. Arattano, F. Comiti, P. Macconi, L. Marchi, Journal of Geophysical Research: Earth Surface, **124**(6), 1440-1463 (2019)
6. G. Nagl, J. Hübl, R. Kaitna, Landslides, **19**(1), 211-220 (2022)
7. F. Comiti, L. Marchi, P. Macconi, M. Arattano, G. Bertoldi, M. Borga, F. Brardinoni, M. Cavalli, V. D'Agostino, D. Penna, J. Theule, J., Nat. Haz, **73**(3), 1175-1198 (2014)
8. V. Coviello, J.I.Theule, S. Crema, M. Arattano, F. Comiti, M. Cavalli, A. Lucía, P. Macconi, L. Marchi. Environ. Eng. Geosci., **27**(1), 95-111 (2021)
9. E. Ioriatti, V. Coviello, M. Berti, F. Comiti, Study of debris-flow initiation through the analysis of seismic signals, submitted to DFHM8 conference (2022)
10. T. R. H. Davies, Acta Mechanica, **63**(1), 161-178 (1986)
11. B. Zanuttigh, A Lamberti, Rev. Geophys., 45, RG3006 (2007)
12. J. Huebl, R. Kaitna, Environ. Eng. Geosci., **27**(2), 213–220 (2021).
13. O. Navratil, F. Liébault, H. Bellot, E. Travaglini, J. Theule, G. Chambon, D. Laigle, Geomorphology, **201**, 157–171 (2013)