Study of debris-flow initiation through the analysis of seismic signals

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Abstract. Monitoring data gathered in the headwaters of the Gadria catchment, eastern Italian Alps, have been analysed to study debris-flow initiation. The active channel, located at 2200 m a.s.l., was instrumented with a geophone, a time-lapse video camera and a rain gauge. The peak amplitude and duration of the seismic signals and their frequency content were analysed and compared with video images. Results showed that different seismic sources produced signals with different characteristics and that it is possible to discriminate the most intense runoff by analysing the combination of peak amplitude and duration of the seismic signal. The further development of this research would be to create an algorithm able to automatically classify the seismic sources and identify intense channel processes that can generate debris flows. In perspective, the combination of seismic detection in the initiation area with monitoring just above the infrastructures at risk could represent an effective solution to expand the lead time of an early warning system.

1 Introduction

In mountain regions, debris flows are responsible for major damage to infrastructure and casualties [1, 2]. The population exposed to this hazard has increased with the construction of settlements and transport infrastructures on debris-flow fans [3]. Warning systems based on sensor networks installed along the debris-flow channel have been implemented in some catchments around the world [4]. The weakness of these systems is that they give the alarm only shortly before the debris flow reaches the infrastructures at risk. Regional warning systems based on the exceedance of critical rainfall thresholds, generally defined by Intensity-Duration (I-D) curves, provide a longer lead-time [5, 6]. However, these systems are affected by large spatial uncertainties because it is often not possible to catch rainfall variability in the source areas with an adequate number and distribution of rain gauges [7, 8]. The mechanisms causing the triggering of debris flows are still poorly understood due to the complexity that characterizes the initiation zones. In particular, antecedent moisture conditions, sediment availability, and the evolution in vegetation and soil cover may change the rainfall thresholds previously defined [4, 5, 7]. This study explores whether geophones, i.e. low-cost seismic sensors, could be used in future for detecting initiation processes and developing enhanced debris-flow warning systems.

2 Study area

The Gadria catchment is located in the Vinschgau – Venosta Valley, in the north-eastern Italian Alps and is part of the Etsch-Adige River basin. The elevation of the catchment ranges from 1394 to 2945 m a.s.l. and its drainage area is 6.3 km^2 [9]. It is bordered on the West by the Strimm catchment, which enters the Gadria stream just before a retention check dam that was built to protect the downstream settlements from debris flows (Figure 1a). The lithology of the basin shows the presence of paragneiss and orthogneiss formed by metamorphism during the Permian and Cretaceous periods. These metamorphic rocks are highly fractured and particularly susceptible to the weather agents. The upper and intermediate sections of the catchments are characterized by colluvial processes, which fill the channels with sediments through rockfalls, debris slides and dry raveling. The basin is prone to a chronic debris-flow activity with one to two debris flows and several small-magnitude floods per year [9, 10].

3 Material and methods

An active channel in the headwaters of the Gadria catchment has been selected for monitoring channel processes related to debris-flow initiation with a rain gauge, a time-lapse video camera and a geophone. The specific goals of the monitoring are the following:
- Investigate whether it is possible to classify different seismic sources (channel processes, earthquakes, wind,

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rainfall, the passage of animals) based on the characteristics of the seismic waves they produce;

- Discriminate between seismic signals produced by runoff, debris flows, or other processes (earthquakes, wind gusts, rainfall or animals) by means of simple signal metrics (i.e., signal duration, peak amplitude and main frequency).

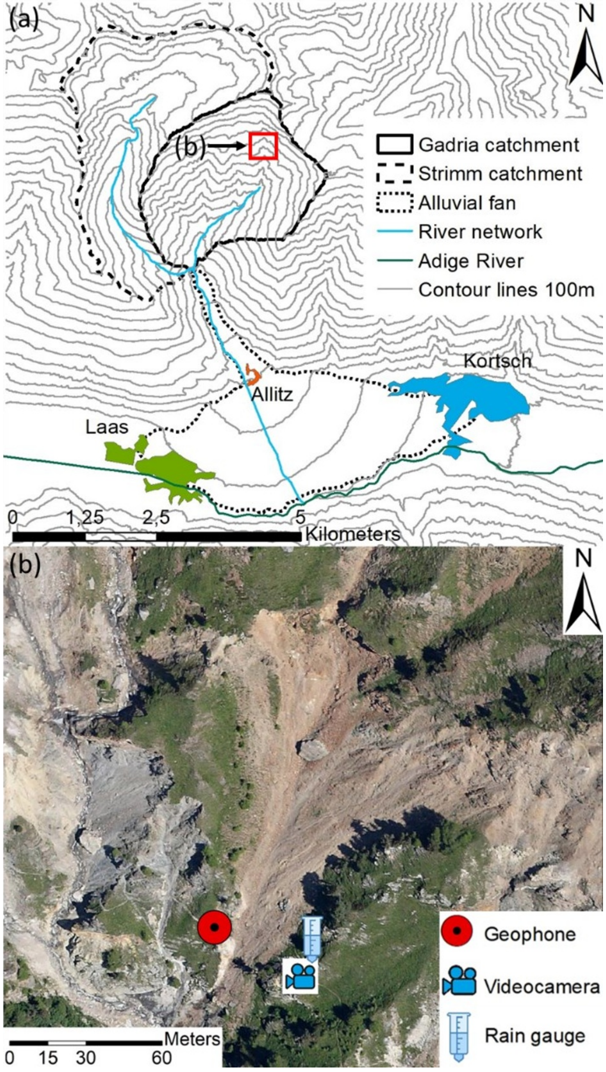

Fig. 1. (a) Map showing the Gadria and Strimm catchments and their river network, the alluvial fan, the Etsch-Adige River and the settlements of Laas, Allitz and Kortsch. (b) Instrumented channel in the upper monitoring station.

3.1 Monitoring of source areas

One of the most active steep channels located in the source area of the Gadria catchment is monitored since 2018. The "upper" monitoring station, located at about 2200m a.s.l., was installed to study the triggering processes and initiation conditions for debris flows [7]. The data examined in the present study have been acquired in July and August 2019 with three instruments installed close to the channel: a time-lapse video camera and a tipping-bucket rain gauge installed on the left bank, and a geophone installed on the right bank (Figure 1b). The video camera points upstream and it is used to record videos suitable to recognize the different flow processes. The videos start when the precipitation recorded by the rain gauge exceeds a very-low threshold of 0.6 mm/min and then lasts for 2 hours. Ground vibrations are recorded by a "Raspberry Shake RS4D", version V5. The advantages of this instrument are that it is low-cost and integrates a 4.5-Hz geophone, a 24-bit digitizer, and a computer into a single box [11].

3.2 Analyses of the seismic signals

The seismic signal sampled at 100 sps was filtered below 45 Hz according to the Nyquist–Shannon sampling theorem and above 5 Hz (Figure 2a). Then, the envelope of the signal Ae was calculated as the average of the absolute value of the raw signal over a specific time window (Figure 2b) using the formula [12]:

$$A_e = \frac{\sum_{i=1}^{fs} |v_i|}{fs} \tag{1}$$

where v_i is the ground vibration velocity and fs is the sampling frequency. Amplitude and duration of the seismic signals, and the spectral characteristics of channel processes were analysed to characterize the different processes observed in the area.

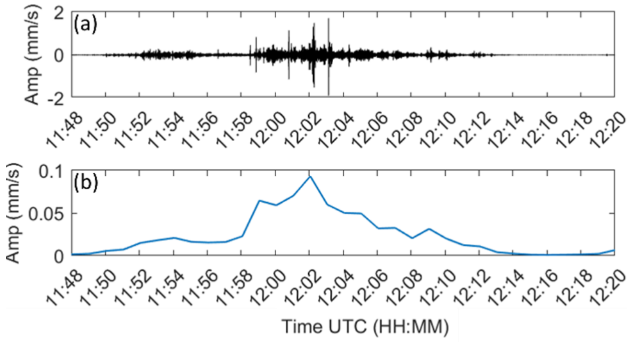

Fig. 2. (a) 5-45 Hz filtered signal; (b) 1-min envelope.

3.3 Classification of seismic sources

Video images were used to identify and classify the sources of the seismic waves recorded by the geophone. The duration and the maximum amplitude of the 5-45 Hz filtered signal related to the sources were extracted. Seismic sources were classified into the three following classes of channel processes:

- Large runoff/ debris flow: strong channel runoff with sediment transport, in some cases associated to surges typical of debris flow.
- Small runoff: channel runoff with limited or absent sediment transport.
- Bank collapse and raveling: mobilization of coarse debris from the channel banks caused by rainfall and raveling of loose sediments down the slope.

Other five sources of seismic noise were also identified:

- Animals: animals captured by the camera while crossing the channel, grazing or jumping.
- Earthquakes: seismic events identified in the national catalog of INGV.
- Wind: wind was identified through the movement of tree canopies.
- Rainfall: precipitation recorded by the rain gauge that exceeds 0.2 mm/5 min.

- Unknown source: signals with low amplitude and long duration whose possible source was not visible in the videos and not related to rainfall.

4 Results

Peak amplitude and duration of the signals produced by the different seismic sources are shown in Figure 3. As can be seen, "large runoff/ debris flow" events show values clearly different from the others in terms of amplitude of the signal. In fact, these signals recorded the highest peak amplitude with values from 0.175 to 1.7 mm/s, while their durations (from about 5 to 11 min) are similar to those of other seismic sources. The most intense event, which occurred on 26th July 2019, produced significant morphological changes in the channel with an estimated erosion depth of 1 m [7]. The two "large runoff/ debris flow" events that affected the entire channel section show a difference of an order of magnitude in the peak amplitude. As shown by the video images, the reason probably lies in the different amount of mobilized material (Figure 4). These results are consistent with the research performed in the lower part of the Gadria catchment by [3] which showed that the amplitude of the seismic signal is positively correlated to the kinetic energy of debris flow, i.e. the flowing mass and its squared velocity. Signal amplitudes of "small runoff" do not differ from "bank collapse and raveling" but the durations are significantly longer allowing to easily distinguish them (Figure 3).

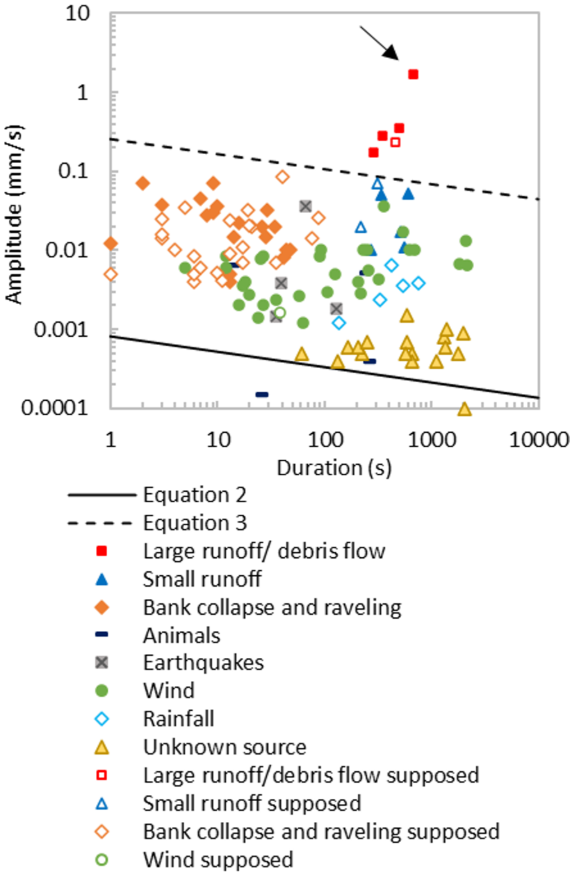

Fig. 3. Scatterplot Peak amplitude Vs Duration of all observed and supposed seismic signals. The black arrow indicates the "large runoff/ debris flow" event that interested the entire channel section on 26th July 2019.

Apparently, it was not possible to distinguish the "large runoff/ debris flow" events from the other channel processes with a simplified frequency analysis, by looking at the main frequency only. However, the spectral analysis confirms that all signals produced by "large runoff/ debris flow" events are characterized by a higher signal power compared to the other seismic sources.

The use of the video camera for the identification of the seismic sources has limitations due to the resolution of the images and the limited framing area. Sometimes, the signal variability suggested that something was happening, but it was not possible to identify the seismic source from the videos. An attempt was made to identify and classify seismic sources only based on the peak amplitude and signal duration. These sources are called "supposed" in Figure 3. The result represents a first attempt of classification only based on the seismic information but independent observations are needed to validate this analysis. For what concerns the only supposed debris-flow signal (Figure 3), field observations confirmed that a debris-flow surge interested the neighbourhood channel. The distribution of the recorded seismic events is characterized by a lower limit represented by:

$$A = 0.0008 * (t)^{-0.192} \tag{2}$$

, where A is the signal amplitude and t the signal duration. 98% of the points are located above equation 2. Adopting an approach similar to rainfall thresholds, the class "large runoff/ debris flow" can be bounded by means of the following empirical equation:

$$A = 0.26 * (t)^{-0.192} \tag{3}$$

, where A is the signal amplitude and t the signal duration (Figure 3). The calculated thresholds highlight the channel response in the upper Gadria. However, signals produced by the 26th-July-2019 event that reached the lower monitoring station (indicated with a black arrow in Figure 3) show a higher intensity compared to all the other observed signals. Therefore, it is expected that the analyses of a longer seismic dataset will allow to define also a threshold that identify the "large runoff/ debris flow" events with high probability of reaching the outlet of the catchment. In perspective, this approach could be adopted to automatically classify the seismic sources recorded in the upper Gadria and identify the most intense channel processes (i.e., large runoff/ debris flows) that can propagate downstream.

5 Conclusions

This study shows how it is possible to recognize different phenomena occurring in the headwaters of a debris-flow basin by looking at the seismic signals they produce. In particular, the combined analysis of peak amplitude and signal duration allowed to discriminate between signals produced by "large runoff/ debris flow" and by other seismic sources. The spectral analysis confirms what was observed in the time-domain: all signals caused by "large runoff/ debris flow" have the highest power content.

Further research is needed to expand the dataset and verify whether these observations are also valid for longer periods and in other sites. A more detailed frequency analysis and the installation of additional monitoring instruments in the adjacent channels may help in the interpretation of seismic signals produced by unknown sources. The same approach should be applied in other catchments to determine the site-specificity of the discriminant. The possible application of this research would be to design an algorithm for the automatic classification of the seismic sources and for the identification of channel processes that can generate debris flows. The identification of intense runoff in the headwaters of the catchment could provide a first alert to local authorities, while a downstream station can confirm the arrival of the debris flow and allow them to close, for instance, transport routes located on debris-flow fans.

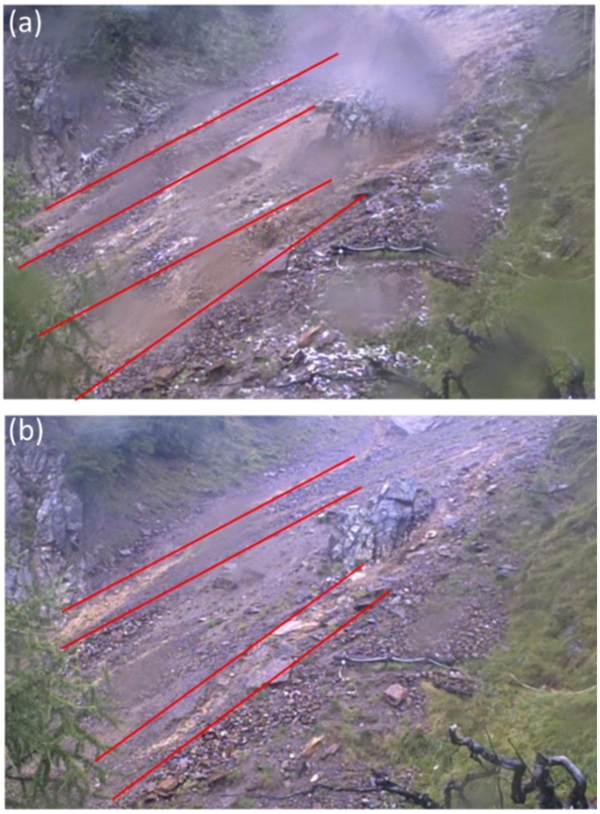

Fig. 4. Time-lapses of debris flows that affected the entire channel section on (a) 26th July 2019 and (b) 6th August 2019.

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