Debris-flow velocity and volume estimations based on seismic data

Andreas Schimmel[1,2], Velio Coviello[1,3], and Francesco Comiti[1]

[1]Free University of Bozen-Bolzano, Faculty of Science and Technology, Italy
[2]Andreas Schimmel - Alpine Monitoring Systems (ALMOSYS), Mkt. Piesting, Austria
[3]Research Institute for Geo-Hydrological Protection, Consiglio Nazionale delle Ricerche, Padova, Italy

Correspondence: Andreas Schimmel (andreas.schimmel@unibz.it)

Abstract. The estimation of debris-flow velocity and volume is a fundamental task for the development of early warning systems, the design of control structures and other mitigation measures. Previous analysis of the seismic energy produced by debris flows showed that the peak amplitudes are representative of the kinetic energy of each surge and debris-flow discharge can be therefore estimated based on seismic signals. Also, the debris-flow velocity can be calculated using seismic data recorded at two spatial separated stations located along the channel by the use of cross-correlation. This work provide a first approach for estimating the ~~total volume of debris flows~~ debris flow volume and velocity based on the seismic signal detected with simple, low-cost geophones installed along the debris-flow channel. The developed methods ~~was~~ were applied to seismic data collected on three different test sites in the Alps: Gadria ~~(IT), Lattenbach (AT), and Cancia (IT)~~and Cancia (Italy), and Lattenbach (Austria). An adaptable cross-correlation time window was used, which can offer a better estimation of the velocity compared to a constant window length. The analyses of the seismic data of 14 debris flows that occurred from 2014 to 2018 shows the strong control of the sampling rate and the sensor-distance on the velocity estimation. A simple approach based on a linear ~~relation between square of the seismic amplitude and the event magnitude~~ relationship between the squares of seismic amplitudes (a proxy for seismic energy) and event volumes is proposed for a first order estimation ~~of the debris-flow magnitude.~~the latters..

1 Introduction

With the rapid socio-economic development of European mountain areas, the automatic detection and identification of mass movements like landslides, debris flows, and avalanches become of paramount importance for risk mitigation. Technological development has rapidly advanced during the last decade, as well as the conceptual advancements brought by former debris-flow research, making the implementation of monitoring devices for research, early warning and alarm purposes more and more effective ~~and feasible~~ (Hürlimann et al., 2019). Past studies showed that such processes induce characteristic seismic and acoustic signals, the latter mostly in the infrasonic spectrum which can thus be used for event detection. Several investigations have already addressed signal processing and detection methods based on seismic (e.g., Coviello et al., 2018; Walter et al., 2017; Burtin et al., 2016) or infrasound sensors (e.g., Zhang et al., 2004; Ulivieri et al., 2012; Marchetti et al., 2019). However, for developing an efficient warning system, not only the detection of events is important but also the identification of the event type (e.g. debris flow vs debris flood) and the estimation of its magnitude and velocity.

An early approach to estimate the process velocity based on seismic data and cross-correlation was proposed by Arattano and Marchi (2005). Later, Havens et al. (2014) and Marchetti et al. (2015) used arrays of infrasound sensors to estimate the velocity of snow avalanches. ~~Whereas~~ Differently, Takezawa et al. (2010) developed a method by which flow velocity is estimated based on the amplification rate of the seismic signals of debris flows. ~~In terms of event volumes,~~ The estimation of the debris-flow magnitude based on seismic data is still an open problem. A quantitative characterization of the event size based on theoretical models (e.g., Lai et al., 2018; Farin et al., 2019) is difficult because of the limited knowledge on the radiated wavefield produced by debris flows and of the uncertainties due to the heterogeneity of the media (Allstadt et al., 2019; Kean et al., 2015) . Some inspiration can be found in the methods used to analyze the seismic signals generated by other processes, such as rockfalls. Manconi et al. (2016) presented an estimation of rockslides volumes based on the ratio between local ~~magnitudes and duration magnitudes~~ and duration magnitude detected by broadband seismic networks. Controlled experiments point to the relationships among the potential energy lost, the kinetic energy and the radiated seismic energy and allow to retrieve the rockfall mass from the seismic signal (Hibert et al., 2017). Le Roy et al. (2019) found a relation between the potential energy of a free-fall rockfall and the seismic energy generated during the impact that allows to estimate the rockfall volume. For debris flows, Coviello et al. (2019) investigated the energy radiated by natural debris flow surges deducing a scaling relation between kinetic and seismic energy. Interestingly, Pérez-Guillén et al. (2019) deduced similar scaling relationships based on seismic parameters to quantify the size of mass flows at Mt. Fuji, Japan, independently from the type of flow (avalanches or lahars) and from the flow path.

~~Given the~~ This scaling relationship suggests that the estimation of debris-flow volumes is possible based on the measured value of flow velocity gathered from a pair of geophones installed along the channel and the seismic energy detected by one of them~~, the magnitude of the debris flow mass could be estimated (Coviello et al., 2019)~~. Despite such recent advances, the estimation of debris flow ~~magnitude~~ volume from seismic data only is a challenging task in the perspective of the real time event characterization, and uncertainties in the volume estimations are still large (Coviello et al., 2019; Pérez-Guillén et al., 2019; Walsh et al., 2012). ~~Most of the few~~ Remarkably, most of the (quite few) studies published so far ~~have addressed single catchments and no universal, simple method to estimate magnitude and flow velocity onlyon seismic amplitudes without external parameters has been developed until now~~on this topic have addressed estimations in single catchments only.

This paper ~~presents a first attempt to overcome the site-specificity inherent in the previous studies by embracing a multiple site analysis, with the aim to test a simple but robust methodology to estimate debris flows and debris floods velocity and magnitude~~ intends to explore the possibility to develop a simple method to predict debris flow velocity and volume based on seismic ~~data, without the need to perform site-specific calibration.~~ sensors, based on limited calibration data. This would enable the method to be easily applicable in different catchments, at least for first order estimations. The aim is not to seek a universal law relating seismic energy to debris flow characteristics, but just to provide robust tools for debris flow risk management.

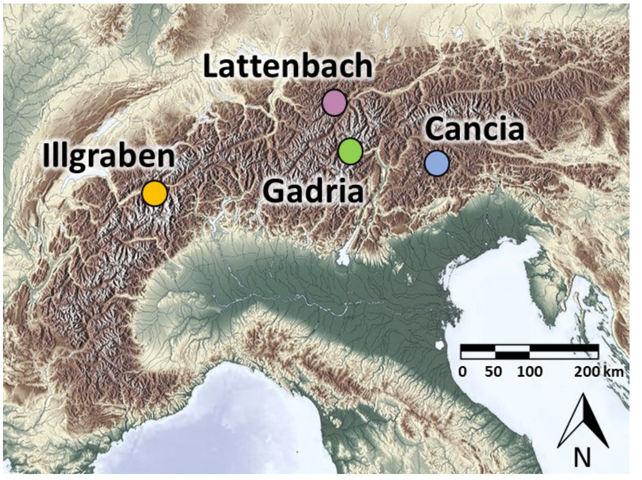

Figure 1. ~~Maps~~ Map showing the ~~three study catchments~~ location of the study catchment.

2 Methods

Data collected in three small catchments located in the European Alps prone to frequent debris flows are analysed here (Figure 1): Gadria (South Tyrol, Italy), Cancia (Veneto, Italy) and Lattenbach (Tyrol, Austria)~~, and Cancia (Belluno, Italy)~~. The data of Illgraben (Vallis, Switzerland) is used to test the developed volume estimation methode.

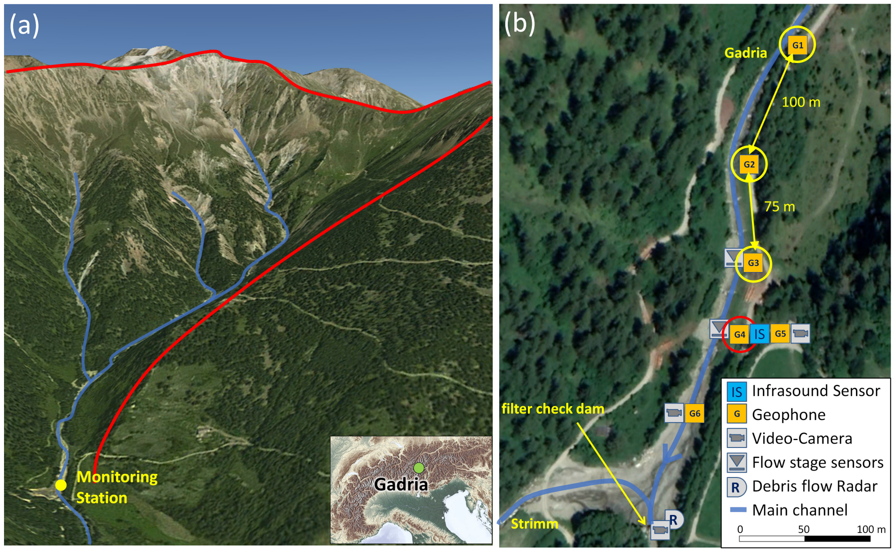

Figure 2. (a) Overview of the ~~test site~~ Gadria site (red line: catchment ~~area~~divide); (b) Closer view of the monitoring station ~~2~~ and sensor setup (background images: ©Google Maps, 2020 (Maxar Technologies)).

The Gadria basin is located in the Vinschgau-Venosta valley, in ~~the North-eastern Italian Alps~~South Tyol (Eastern Italian Alps). It has a catchment area of 6.3 km^2, ranges in elevation from 2,945 m a.s.l down to 1,394 m a.s.l and is characterized by a regular debris-flow activity. The monitoring system consists of rain gauges, flow stage sensors, geophones, video cameras, piezometers and soil moisture probes. Debris flow depth is monitored by radar sensors installed at three cross-sections along the main channel. A linear array of geophones is used for event detection based on a STA/LTA algorithm (Coviello et al., 2019) and this geophone data can also be used to calculate the velocity. Figure 2 gives an overview of the catchment and the monitoring setup. The geophones G1~~and~~ , G2 and G3 used for the calculation of the velocity (marked with a yellow circle) are placed in a distance of 100 m (G1,G2) and 75 m (G2,G3) along the channel. The geophone G4 (marked with a red circle) used for the ~~magnitude~~ volume estimation is part of a debris flow detection system based on a combination of infrasound and seismic sensors. This detection system (MAMODIS) consists of one infrasound sensor, one geophone and a microcontroller, where a specially designed detection algorithm is executed which reliable detects events in real time directly at the sensor site (Schimmel and Hübl, 2016; Schimmel et al., 2018).

The ~~Lattenbach Creek (district of Landeck, Tyrol) has a catchment area of 5.3 and is a monitoring site for debris flows operated by the Institute of Mountain Risk Engineering at the University of Natural Resources and Life Sciences, Vienna (Hübl and Moser, 2006). Three monitoring stations are installed along the channel (Figure 4), and these are equipped with flow height (radar gauges), geophones, video cameras, 2D-Laser scanner. The station "Darwinalpe" is a meteorological monitoring station. At the middle monitoring station, a debris flow Pulse-Doppler Radar can be used for measuring the surface velocity. Near this radar, two stations for testing the warning system MAMODIS are installed at a distance of 90 . The geophone data of~~

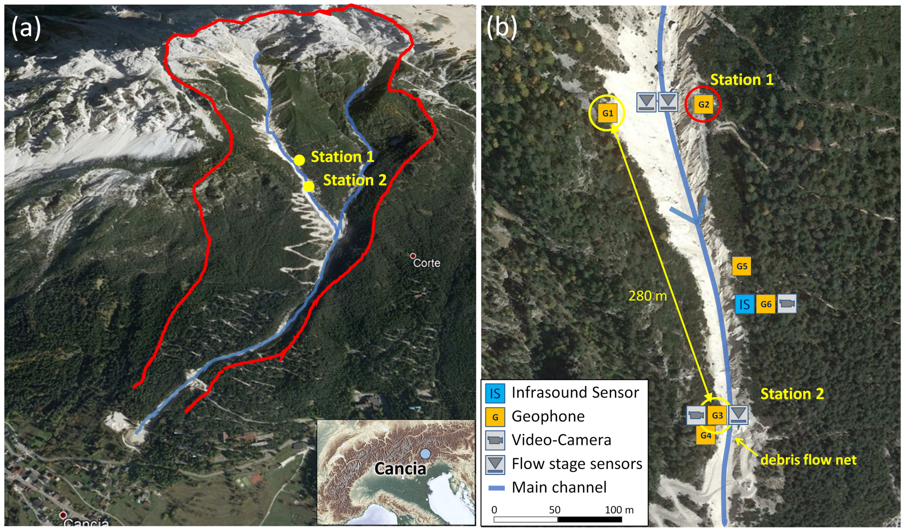

Figure 3. (a) Overview of the ~~test site~~ Cancia site (red line: catchment ~~area~~divide); (b) Closer view of the monitoring ~~station 2~~ stations and sensor setup (background images: ©Google Maps, 2020 (CNES, Airbus)).

~~these two stations (G1 and G2) are used to calculate the debris flow velocity and the lower one (G2) is used for the magnitude estimation in this study.~~

~~(a) Overview of the test site Lattenbach (red line: catchment area); (b) Closer view of the monitoring station 1 and 2 and sensor setup (background images: ©Google Maps, 2020 (Maxar Technologies)).~~

~~Finally, the~~ Cancia channel is located in the Dolomites within the ~~Veneto Region~~ Province of Belluno(Italy)~~with~~ , and the catchment features an area of 2.5 km^2 on the southwestern slope of Mount Antelao (3264 m a.s.l.)~~It~~ . The catchment ranges in elevation between the Salvella Fork at 2500 m a.s.l. down to a retaining basin at the village of Cancia at 1001 m a.s.l. (Gregoretti et al., 2019). The data used for the ~~magnitude~~ volume estimation and velocity calculation are recorded by the geophones installed at station ~~2 and 3~~ 1 and 2 belonging to the monitoring and warning system designed by the company CAE (CAE, 2014; Cavalli et al., 2020). Geophone G1 and G3 are used for the velocity estimation and geophone G2 is used for the ~~magnitude~~ volume estimation. Beside a monitoring system of the company CAE, three monitoring stations have been installed by ~~UNIBZ and the Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Universitá di Bologna~~ Universities of Padova, Bologna and Bolzano in 2019 (Figure 3a). This monitoring stations include two laser stage sensors, two rain gauges, several time-lapse cameras, geophones and the infrasound/seismic detection system MAMODIS and integrates a monitoring network that was operational in the previous years only for scientific purposes (Simoni et al., 2015).

Finally, the Lattenbach Creek (district of Landeck, Tyrol) has a catchment area of 5.3 km^2 and is a monitoring site for debris flows operated by the Institute of Mountain Risk Engineering at the University of Natural Resources and Life Sciences, Vienna (Hübl and Moser, 2006). Three monitoring stations are installed along the channel (Figure 4), and these are equipped with flow height (radar gauges), geophones, video cameras, 2D-Laser scanner. At the middle monitoring station, a debris flow

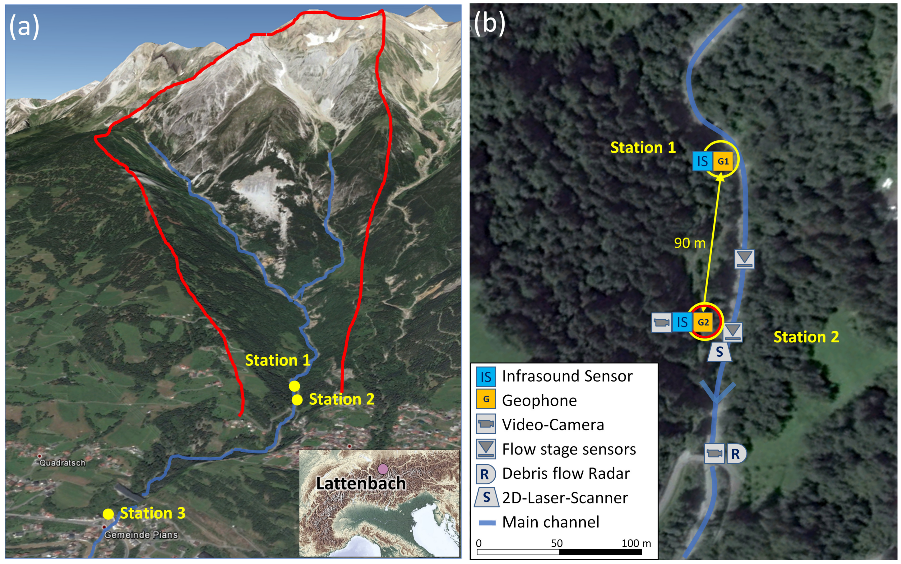

Figure 4. (a) Overview of the Lattenbach site (red line: catchment divide); (b) Closer view of the monitoring stations and sensor setup (background images: ©Google Maps, 2020 (Maxar Technologies)).

Pulse-Doppler Radar can be used for measuring the surface velocity. Near this radar, two stations for testing the warning system MAMODIS are installed at a distance of 90 m. The geophone data of these two stations (G1 and G2) are used to calculate the debris flow velocity and the lower one (G2) is used for the volume estimation in this study.

Table 1 gives an overview of the seismic sensors used at the different sites. The seismic amplitudes used for this study are calculated every second from the seismic data recorded at the reported sampling rates. At Cancia, an internal ~~sample~~ sampling rate of 500 Hz is used, but the available seismic data are recorded as 0.1 Hz max. amplitude values. For the geophones of the type SG-5 and SM-6 ~~geophones~~ amplitude values of 1 Hz are calculated from the raw signals sampled at 100 Hz and at Gadria the used data for this study are 0.5 Hz amplitude values.

2.1 Velocity estimation

The estimation of ~~the~~ debris flow velocity is carried out by the time-distance method, whereby velocity is calculated as the distance between two stations measuring seismic amplitude along the channel divided by the time difference of the two signals calculated from amplitude maximum values (Coviello et al., 2021; Schimmel et al., 2018), or by cross-correlation of the two seismic signals (Arattano et al., 2012). The result of this method is a mean surge velocity (celerity). To obtain the time difference based on amplitude maxima, the signal is manually analysed identifying comparable peaks (i.e., representing the debris flow front or subsequent surges) in the signals recoded at the two stations. The manual analysis is only used for validating the results of application of the cross-correlation method in this paper. For the cross-correlation ~~, three~~ analysis, the analysis window size has to be selected. After testing several settings, we decided to use a starting window size related to the distance

Table 1. Summary of the seismic monitoring equipment

	Geophone	Type	Natural freq. [Hz]	Sensitivity [Vsm^{-1}]	Sampling rate [Hz]	Amp. values [Hz]
Lattenbach	G1/2	Sercel SG-5	5	80	100	1
Gadria	G1/2/3	Geospace	10	85.8	128	0.5
	G4	Sercel SG-5	5	80	100	1
	G5/6	Sensor NL SM-6	4.5	28.8	100	1
Cancia	G1/2/3/4	SolGeo VELOGET-DNL-H	14	18.2	500	0.1
	G5/6	Sensor NL SM-6	4.5	28.8	100	1

of the two geophones. This choice offers the best result for the cross-correlation and provides an objective method, based on one parameter (distance) only, to adapt the cross-correlation analysis at new sites. Number of samples equal distance means that a resolution from 1 ms^{-1} is possible which seems to be a phyisically meaningful starting value for describing turbulent debris flows. Three different sliding time ~~windows~~ window sizes are used because an adaptation of the time window ensures better results for the cross-correlation ~~during the whole flow (from turbulent to smooth)~~for all flow stages. For choosing the window length, the ~~relation~~ ratio between maximum amplitude and minimum amplitude is analysed in ~~a~~ the starting window size which has a number of samples equal to the distance. Analyses of the seismic data of several events showed ~~, that if the relation is above a limit of~~ that when such ratio >6 ~~, we have a more turbulent flow with a significant signal shape , so the cross correlation can be calculated~~the debris flow features an adequate signal shape for cross-correlation to be adopted. If the ~~relation is below~~ ratio is <6, the window length will be enlarged by another number of samples equal to the distance. If ~~there is still not enough significance in~~ the signal shape still is not suitable, the window will ~~then be enlarged once again. So the lowest~~ be further expanded. Figure 5 shows the principle of the adaptive window sizes. Therefore, the lowes velocity that can be calculated is theoretically 1 ms^{-1} in ~~an turbulent part~~ the first, typically rougher part of the debris flow hydrograph, with a signal length equal the distance, and it could reduce to 0.33 ms^{-1} for the smoother, tail phase of the event if a window length of three times the distance is used. Cross-correlation is performed twice ~~during the window time length~~ with a sliding window~~. The data of the two signals is~~ , since an overlap of the half sample numbers offers most consistent results. The two signals are normalized in the window frame by the maximum amplitude value. Only if the cross-correlation coefficient ~~is above a value equal to~~ exceeds 0.8 the result is kept for the velocity calculation. Since the cross-correlation analyses is ~~done on a data basis of one seconds values, the data of~~ performed at 1 s time steps, the Cancia and Gadria ~~is~~ data are upsampled to a sample rate of 1 Hz. Therefore amplitude values from Cancia and Gadria are ~~used as a constant value~~ constant over 10 s ~~or~~ and 2 s, respectively.

2.2 ~~Magnitude~~ Volume estimation

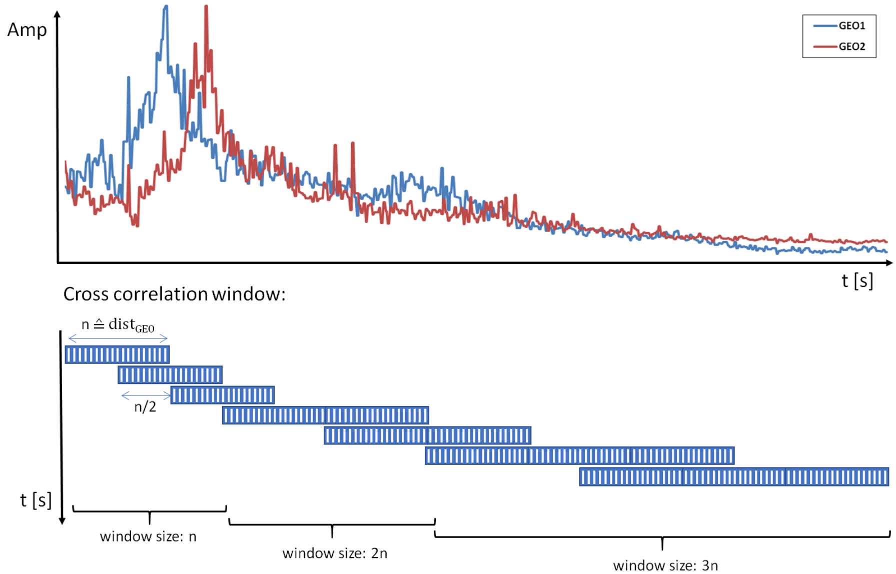

Figure 5. Methode cross-correlation analysis: window sizes and overlaps.

A As reported in the introduction, a linear trend between the seismic energy (J), which is proportional to the square of the seismic amplitude (m^2s^{-2}), and the kinetic energy per unit area produced by debris flows has been observed (Coviello et al., 2019) by Coviello et al. (2019). Consequently, we integrated the squared amplitude values during the whole duration of a debris flow to obtain an estimation of the seismic energy of each event. By comparing these values with the volumes estimated by flow height measurements and velocity estimations (To make the results comparable for all three sites and not depending on different detection methods, the used event duration has been determined manually. Subsequently, we related these integrals of the seismic signal to the associated debris flow volumes. For these latter, we used published and unpublished estimates obtained by several methods (topographic surveys, stage sensors, 2-D scanner 2D scanners and debris flow radar) an approximation for the magnitude can be calculated by curve fitting. in the study basins (Schimmel et al., 2018; Coviello et al., 2021; Simoni et al., 2015) . Overall, a total of 14 events (occurred from 2014 to 2018) are available from the three different catchments (Table 2). The best fit curve relating debris flow volumes to the seismic signal was obtained by performing a linear regression analysis. Remarkably, the performance of the method is tested against 11 independent debris-flow volumes recorded at Illgraben, Switzerland, from 2015 to 2017 (Schimmel et al., 2018; Marchetti et al., 2019). Since all monitoring stations used for this study are rather close to the channel (between 10 and 20 m) and the distances are nearly the same at every test site, we neglected attenuation of the signals in the ground, geometric spreading and the influence of topography or geology. To make data analysis comparable among the sites, the lowest sampling rate (10s for the Cancia dataset) is used, and seismic data from the other catchments are transformed in terms of maximum values of amplitude over periods of 10s.

Table 2. List of event dates and volumes for all sites. Data gathered in Gadria, Cancia and Lattenbach were used to retreive the empirical equation 1 while data from Illgraben for validation, see Figure 10.

	Date	tot. Volume [m^3]	Duration [s]	Reference
Lattenbach	09.08.15	11500	1600	Schimmel et al. (2018)
	10.08.15	18500	2800	Schimmel et al. (2018)
	16.08.15	5000	1200	Schimmel et al. (2018)
	10.09.16	46000	3900	Schimmel et al. (2018)
	29.07.17	14000	1600	internal report
	30.07.17	41000	3500	internal report
Gadria	15.07.14	11600	2000	Coviello et al. (2021)
	08.06.15	12600	3300	Coviello et al. (2021)
	12.07.16	2400	2500	Coviello et al. (2021)
	19.08.17	2300	1400	Coviello et al. (2021)
Cancia	23.07.15	25000	1600	Simoni et al. (2015)
	04.08.15	20000	2000	Simoni et al. (2015)
	01.08.18	4500	2700	Simoni et al. (2015)
	29.10.18	11000	3200	Simoni et al. (2015)
Illgraben	22.07.15	8700	3500	Schimmel et al. (2018)
	10.08.15	6100	6700	Schimmel et al. (2018)
	14.08.15	25000	9500	Schimmel et al. (2018)
	15.08.15	2000	5500	Schimmel et al. (2018)
	12.07.16	10000	4200	Schimmel et al. (2018)
	12.07.16	60000	3000	Schimmel et al. (2018)
	22.07.16	>10000	3000	Schimmel et al. (2018)
	09.08.16	<10000	2500	Schimmel et al. (2018)
	29.05.17	70000	3500	Marchetti et al. (2019)
	04.06.17	24000	2800	Marchetti et al. (2019)
	14.06.17	33000	3100	Marchetti et al. (2019)

3 Results

3.1 Velocity estimation

Here First we present the results obtained about velocity estimation adopting the methods described above, applied to three debris flows events recorded in different catchments. Figure 6 illustrates velocity estimations applied on to the Lattenbach event occurred on 30. July 2017, which featured a peak discharge of 88 $\mathrm{m^3s^{-1}}$, a total volume of 41,100 $\mathrm{m^3}$ and an overall duration of around 3500 s.

This debris flow had a front about 1.3 m high, and the velocity (3.5 to 4.7 $\mathrm{ms^{-1}}$) calculated by using the time difference between maximum amplitude values results very similar to the velocity calculated by cross-correlation with 4 $\mathrm{ms^{-1}}$. For the peak discharge (flow height exceeding 3.5 m, the velocity calculated by means of maximum values turns out slightly higher (10 $\mathrm{ms^{-1}}$) than the one (9 $\mathrm{ms^{-1}}$) determined by cross-correlation. During the following part of the event (i.e., after 2500 s) no significant surges could be found to calculate flow velocities using maximum values, and the cross-correlation most likely leads to overestimating velocities.

Figure 7 displays the seismic signals and the velocity estimation for a debris flow occurred in the Gadria on 08. June 2015, which was characterized by a total volume of 12,600 $\mathrm{m^3}$.

The event is composed of several surges in the range 1-1.5 m flow height. The front velocity and the velocity of the surge visible at 2000 s seems to be overestimated by the cross-correlation method, because velocities over 9 $\mathrm{ms^{-1}}$ and 7 $\mathrm{ms^{-1}}$ respectively seem unrealistically high based on previous results from the Gadria (Theule et al., 2018; Coviello et al., 2021). In contrast, for the other surges, flow velocities calculated based on maximum values and cross-correlation give consistent estimates, around 5 $\mathrm{ms^{-1}}$.

Finally, Figure 8 shows the case of a debris flow in the Cancia channel. This event was recorded on 01. July 2020. While the debris flows height reaches 2.4 m, flow velocities for this event appear to be lower (max. 3.2 $\mathrm{ms^{-1}}$) than in the case of Lattenbach and Gadria.

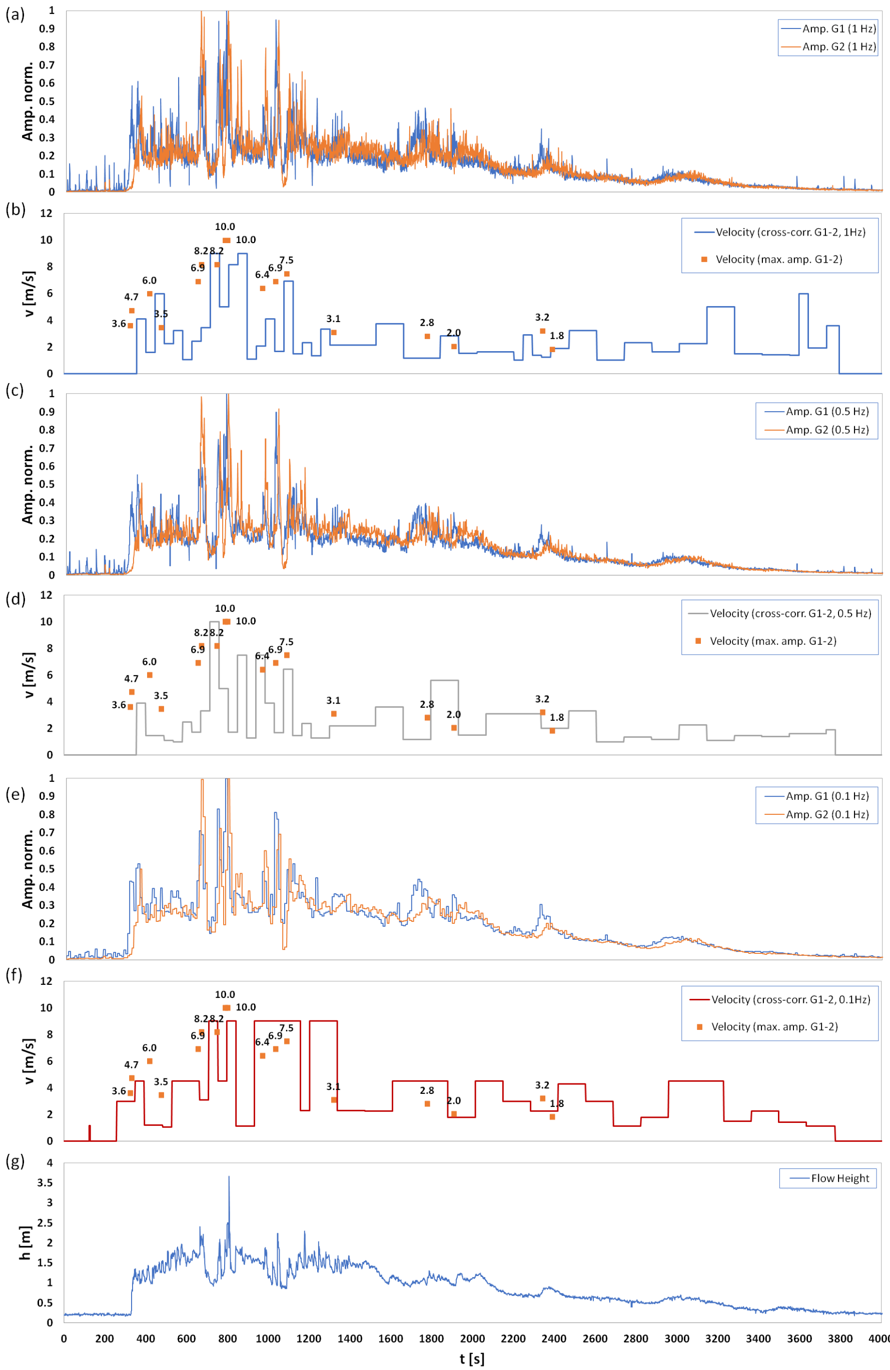

Figure 6. Debris flow at Lattenbach on 30. July 2017: (a,c,e) ~~Normalized~~ normalized amplitudes of the two geophones (G1,G2), (~~b~~g) flow height, (~~e~~b,d,e) velocity estimation based on maximum values and cross-correlation (compared for sampling rates of ~~the debris flow at Lattenbach on 30. July 2017~~1 Hz, 0.5 Hz and 0.1 Hz)

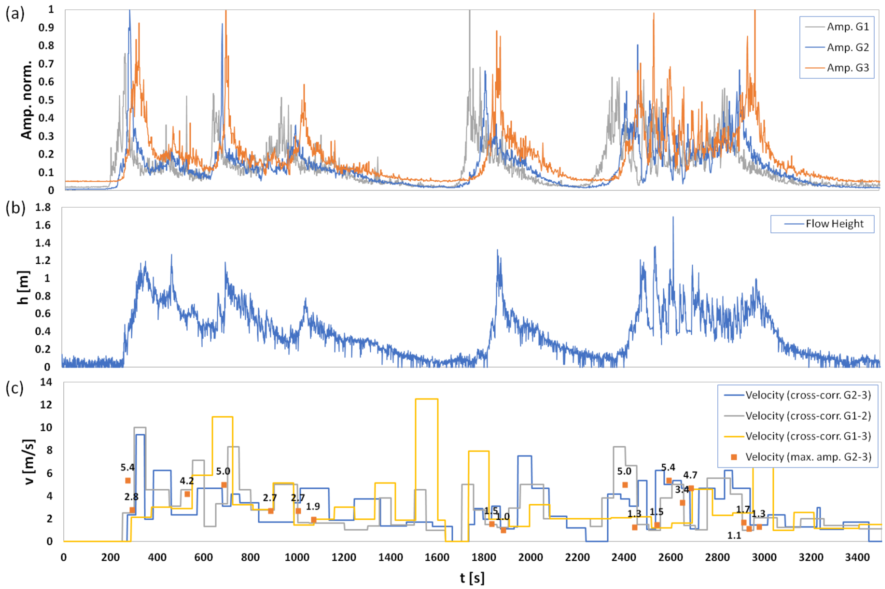

Figure 7. Debris flow at Gadria on 08. June 2015: (a) Normalized amplitudes of the ~~two~~ three geophones (G1,G2,G3), (b) flow height, (c) velocity estimation based on maximum values and cross-correlation~~of the debris flow at Gadria on 08. June 2015~~

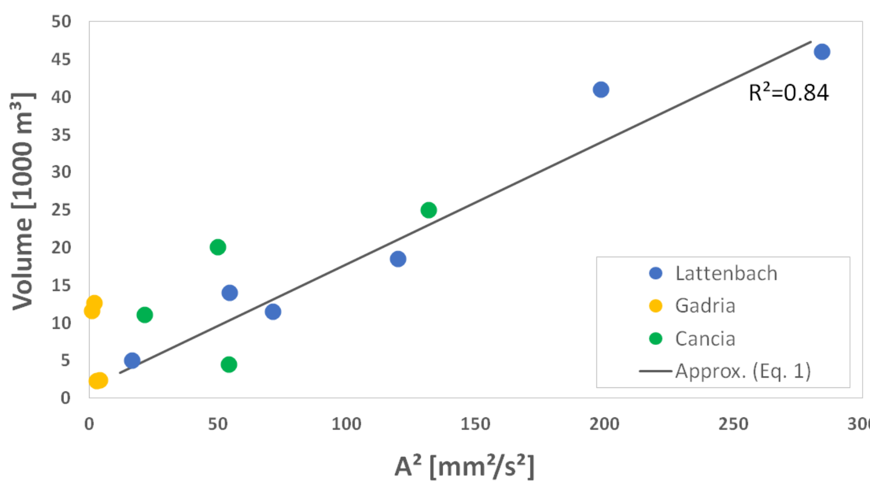

Figure 8. Debris flow at Cancia on 01. July 2020: (a) ~~Normalized~~ normalized amplitudes of the two geophones (G1,G3), (b) flow height, (c) velocity estimation based on maximum values and cross-correlation~~of the debris flow at Cancia on 01. July 2020~~

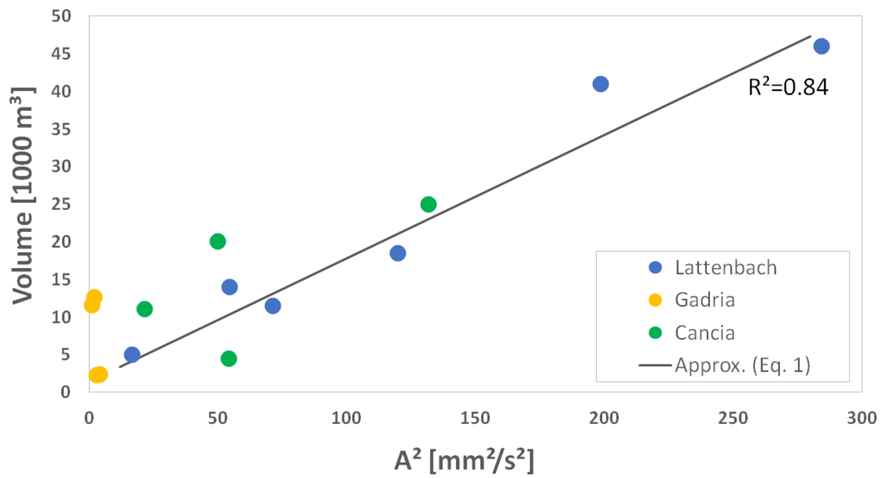

Figure 9. Relationship between squared integrated seismic amplitude and total volume based of the debris flow events listed in Table 2 (from Gadria, Lattenbach and Cancia)

3.1 ~~Volumes estimation~~

To test the methodology described above for the estimation of debris flow volumes based on seismic signals, a total of 14 events (occurred from 2014 to 2018) are available from the three different catchments (Table 2).

~~List of event dates and volumes for all sites Datetot. Volume Duration Lattenbach09.08.1511500160010.08.1518500280016.08.155000012~~

~~To make data analysis comparable among the sites, the lowest sampling rate (10 for the Cancia dataset) is used, and seismic data from the other catchments are transformed in terms of maximum values of amplitude over periods of 10 .~~ The method is tested against 11 independent debris-flow volumes recorded at Illgraben, Switzerland, from 2015 to 2017. Figures 9 shows that the use of the squared seismic amplitudes (A^2 in $\mathrm{mm^2 s^{-2}}$) with a linear fitting seems most promising to provide a preliminary estimate of event volumes (V_{tot} in $\mathrm{m^3}$) compared to other curve fitting approaches like power law ($R^2 = 0.56$) and exponential fitting ($R^2 = 0.57$). The best fitting linear equation reads:

$$V_{tot} = 164\,A^2 + 1419 \quad (1)$$

Figure 10 compares the observed values (~~horizontal~~ vertical axis) for total volume to the predicted values (~~vertical~~ horizontal axis) according to Eq. 1. Two events at Illgraben plot out quite far off the confidence level shown in Figure 10. Possible reasons for the poor prediction of their volumes by Eq. 1 will be provided in the discussions.

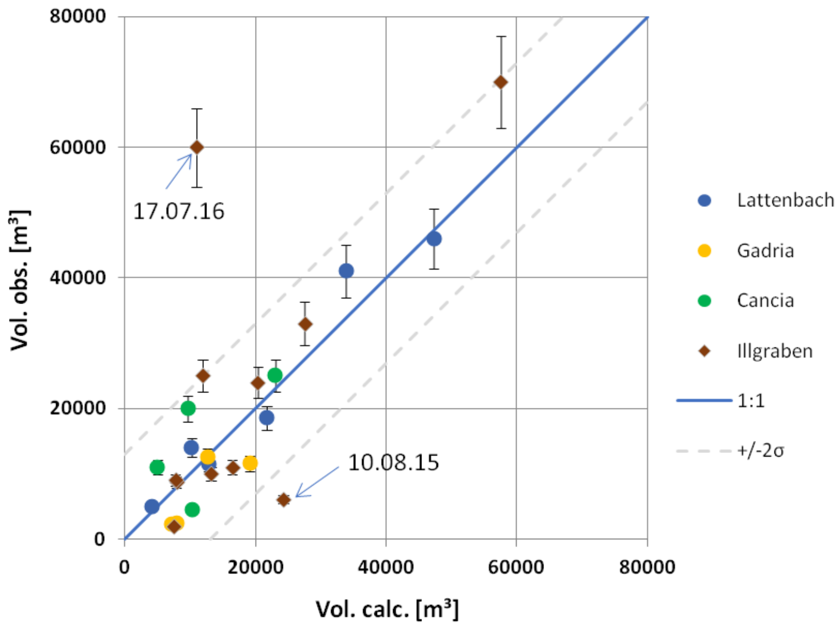

Figure 10. Comparison of the predicted volume vs observed volume. The dark blue line represents the one-to-one relationship and the ~~light blue area indicates a 20% error range~~dashed lines represent the confidence interval of the distribution.

4 Discussion

Arattano et al. (2012) showed ~~,~~ that the cross-correlation technique applied on seismic signals can be an useful tool to analyze ~~the flow behaviour of debris flows~~ debris flows kinematics. Even when no clearly-defined signal features like a well-defined main front in the debris flow wave is present, the cross-correlation can ~~help to get a good estimation of the velocity. But also for the cross-correlation~~ provide reliable estimation of velocity. Nonetheless, some significant signal features are required. Our results suggest that the cross-correlation method we used - based on a window length adaptable according to the signal waveform - provide solid estimates of debris-flow velocity, as temporal resolution is high during the ~~most turbulent, faststage~~ fast, initial stages of the flow, while longer window length are applied for smoother flows, thus permitting to avoid wrong correlation results.

Importantly, our study benefited from three, quite different test sites. The influence of different distances between the geophones is evident. The longitudinal geophone distance in the Gadria (75 m) and Lattenbach (90 m) appear to be appropriate for fast debris flows, while the longer distance in Cancia (280 m) makes ~~harder and more unreliable~~ difficult or even impossible capturing the same surges at different sensors. However, a longer distance offers the possibility to use higher resolution for the velocity calculation. In any case, the transversal distance between the channel and the geophones should be much smaller (at least the half) than the longitudinal distance between the two geophones (Coviello et al., 2019). The distance has to be chosen to ~~get~~ provide a significant difference in the signals in an appropriate time, so that the cross-correlation offers ~~useful results for the calculation of the~~ valid results for flow velocity.

The sampling rate also has an important effect on the reliability of velocity estimations. At Lattenbach and Gadria, one amplitude value every 1-2 s was available. This seems to be a proper sampling in combination with the sensor distances. At Cancia, only one sample ~~per~~ every 10 s is available, so that the signal shapes can be very different at the two geophones, ~~which can determine~~ determining problems for the cross-correlation analysis. In fact, surges can be missed and such a low sampling rate coupled with the long distance lead to an exaggerated ~~- i.e., not useful -~~ averaging of flow velocity of different surges. This might has an effect on the calculated velocity values in Cancia, which are much lower compared to the other sites. ~~But~~ However, in Cancia velocities estimated on the basis of image analysis of time-lapse videos on previous events (Simoni et al., 2015) ~~showed similar results~~ are in the same range (e.g. 1.5 to 4 ms^{-1} for a debris flow on 23. July 2015). ~~So~~ Therefore we believe that the lower velocities in Cancia compared to Gadria and Lattenbach ~~seems to be caused by the flow regime of the events~~stem for the different characteristcs of debris flows of this catchment, which are more granular compared to the other sites.

We performed a test on the debris-flow event recorded at Lattenbach on 30. July 2017 (Figure 6). Seismic data of this event were recorded at 1 Hz. We subsampled data at at 0.5 and 0.1 Hz and we compared the flow velocity calculated on these three signals. Figure 6 shows remarkable differences when adopting the the cross-correlation technique at different sampling rate. Apart from the obiviously larger duration of the time windows, the signal subsampled at 0.1 Hz produces an overestimation of the flow velocity of the main surges (i.e., from t = 500 to t = 1500 s) compared to the original signal.

Different sensors other than the geophones can be used to determine debris flow velocity. So instead of geophones two separated stage sensors can be used for the time-distance method. The advantage of stage sensors is that they measure the process directly, so there are no effects of ground damping, channel texture or the viscosity of the process, which have a high influence on the seismic signal shape. On the other side, stage sensors need a structure above the channel, so they have a much higher installation effort and are more exposed to the ~~process~~ debris flow (Coviello et al., 2019). Alternatively, flow velocity can be measured by ~~Pus~~ Pulse Doppler radar (Koschuch et al., 2015). This method calculates the velocity from the frequency shift of a pulse-modulated high-frequency reflected radar signal, which is proportional to the velocity of the moving object (Doppler effect). The detection area is divided in different range gates and the result is an instantaneous surface velocity distribution (velocity spectrum) for each range gate. Therefore, a debris flow radar measures the velocity directly, but there is an averaging over the range gate, so the surge velocity measured by the radar is often lower than the surge velocity measured by the time-distance method.

~~The results of the magnitude estimation show that there is a~~ A linear trend between the square of the seismic amplitudes and the debris flow ~~magnitudes. Both diagrams (Figure 9 and 10)~~ volumes is apparent from analysis conducted by merging the three sites. The fact that a linear model performs definitely better than others (power law and exponential, as reported in the Results) is in agreement with the physical processes linking seismic energy to debris flow mass, as already noted by Coviello et al. (2019). Figure 10 compares the observed values (vertical axis) of total volume to the predicted values (horizontal axis) of all the debris flow events reported in Table 2. Data gathered at Gadria, Cancia and Lattenbach represent the test dataset while the validation dataset is composed of debris flows observed in the Illgraben catchment, Switzerland, from 2015 to 2017. This analysis suggest that it ~~may be~~ is possible to obtain first-order estimates of ~~the total volume for debris flows~~ debris flow volumes based on the seismic amplitudes, but there is still a large variance, since there are several factors affecting the seismic signals: distance geophone - channel, damping in the ground or sampling rate ~~.~~ (e.g., Kean et al., 2015; Coviello et al., 2018; Allstadt et al., 2019). As already highlighted in the results, two events in the Illgraben out of eleven that compose the validation dataset (debris flows observed at Illgraben) plot out of the confidence interval of the distribution (2 σ). The error in the volume prediction of the 10. August 2015 event is possibly due to the significantly higher velocity of this event compared to the others (Schimmel et al., 2018). Indeed, the volume prediction is strongly controlled by the velocity and the mass (i.e., solid content) of the mixture (Coviello et al., 2019). Concerning the other outlier (12. July 2016 debrs flow), the velocity of the first surge was high (7.8 $\mathrm{ms^{-1}}$) but in the video recording the first part of the flow appears very liquid and the tail viscous. This can explains the low amplitudes of the geophone signal that generate such a small volume when using equation 1. Additionally, the total volume is estimated ~~by the sum~~ over the event duration ~~,~~ ~~so~~ and for an automatic ~~magnitude estimation this~~ volume estimation such event duration is defined by the detection method itself. For example, the amplitude thresholds for the detection criteria has also an influence on the event duration and thus on the total volume estimation.

~~With such a model, it could be possible to estimate in near real time the volume of~~ Nonetheless, adopting such a phyisically-sound empirical model, a ~~debris-flow surge~~near-real time estimate of debris flow surges is possible. However, this volume estimation becomes available only at the end of the surge. This means that the final volume estimation would be provided too late to inform civil protection managers about the flow ~~magnitude~~volume. Therefore, this method is still quite far from the goal of having a real time, accurate ~~magnitude~~ volume estimation to be implemented in early warning systems. However, the method could provide a rough estimate on event ~~magnitude~~ volume to be promptly used by local authorities for managing the debris flow event, e.g., by rapidly planning clearing of retention basins and bridges and roads likely to be obstructed and flooded.

Studies of different events also showed a large dependency of the seismic amplitudes and their frequency spectrum on the velocity of the ~~process~~debris flow. For example, Lai et al. (2018) presents a model where the seismic amplitudes are most sensitive to the product of four physical parameters related to the debris flow: length and width of the boulder snout, grain size cubed, and average speed cubed. This model and also the model presented by Farin et al. (2019) shows that a method including the estimation of the ~~process velocity and sediment concentration~~ debris flow velocity and grain size distribution can result in a more accurate calculation of ~~the magnitude~~debris flow volume. The influence of the sediment concentration on the seismic data can therefore improve the results of the ~~magnitude~~ volume estimation, but there is still no method to automatically estimate the sediment concentration on seismic data, which could be implemented in the ~~magnitude~~ volume estimation. Currently it is only possible to differ between debris flow and debris floods based on the infrasound or seismic peak frequencies (e.g., Hübl et al., 2013), but this ~~has still~~ still poses high uncertainties and is far ~~off from an useful estimation of the~~ from providing reliable estimation of sediment concentration.

5 Conclusions

This work shows that important differences can be observed in the debris flow velocity estimation among the different ~~methods deployed and~~ sensor setups at the different catchments. The optimal distance between the sensors, the best sample rate for cross-correlation, or the analysed frequency range has an important influence of the quality of the results. The presented approach with a cross-correlation window ~~size adopted~~ length adapted to the signal ~~shape shows promising results, but still further research on different events and sites are necessary to get a robust velocity estimation method~~waveform improves velocity estimation over the entire debris flow duration (from fast, initial stages to smoother flows).

The ~~results of the magnitude estimation showed, that it is possible to estimate the total volume of events based on the seismic data but it still shows high uncertainties and improvements of this method~~ estimation of the debris-flow magnitude based on seismic data is still an open problem as theoretical models are still affected by large uncertainties. Starting from the relation between kinetic and seismic energy, our experimental results show that debris flow volumes can be reasonably - within a +- 20% error in most cases - estimated from seismic data only, by adopting a linear model based on the squares of the seismic amplitude. However, improvements are necessary for an automatic ~~magnitude~~ volume identification usable for a warning system. ~~Beside~~ In fact, beside the magnitude, ~~the~~ flow velocity and the sediment concentration ~~has~~ have also a large influence on the seismic amplitudes of a debris flow, so including ~~this~~ them in the magnitude estimation could ~~offer a more accurate approach.~~lead to more accurate results..

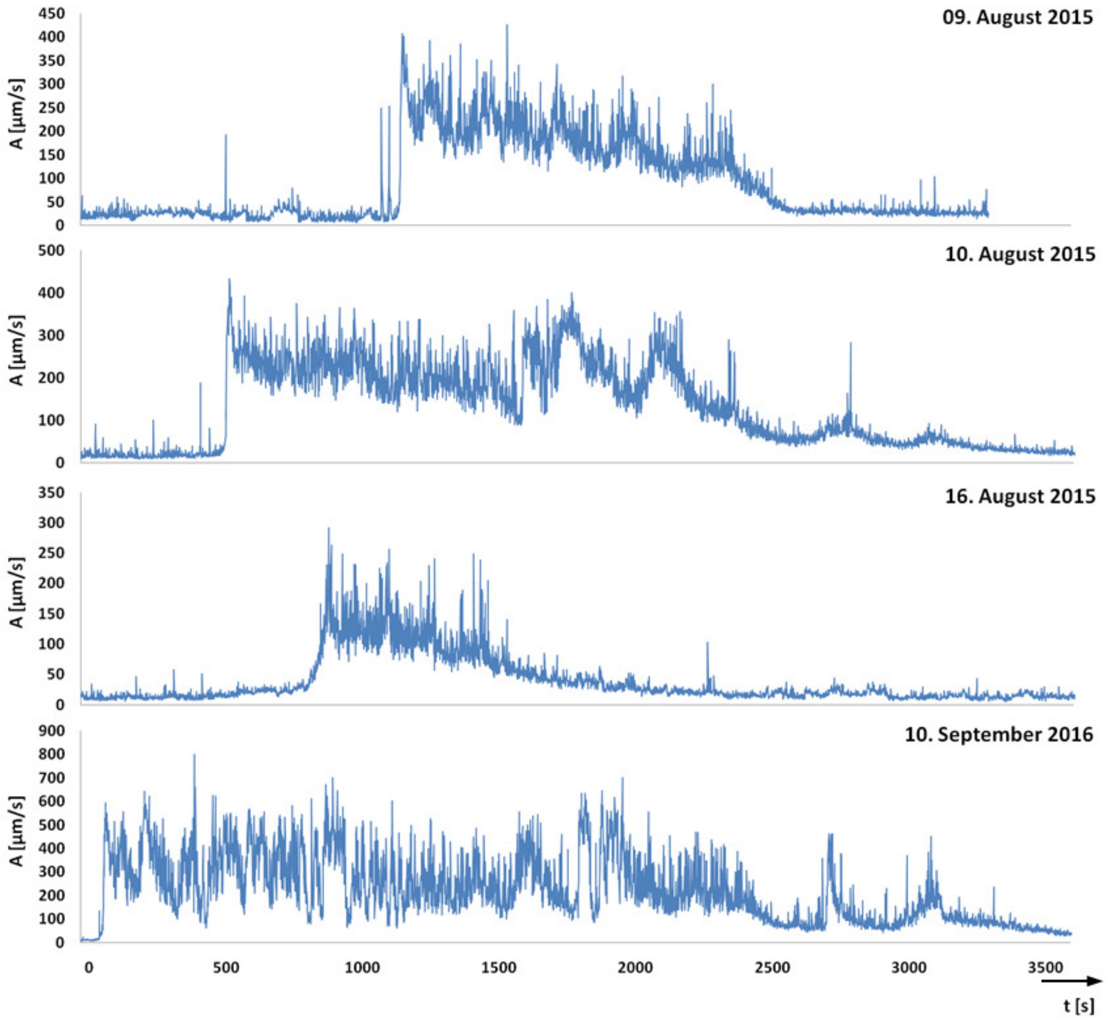

Figure A1. Seismic amplitudes of debris flows at Lattenbach (2015 - 2016)

Data availability. For access to the dataset please contact andreas.schimmel@unibz.it

Appendix A: Events from 2014 to 2018

290 This appendix gives an overview of the seismic signals recorded of debris flows which occurred at the catchments Lattenbach, Gadria and Cancia from 2014 to 2018.

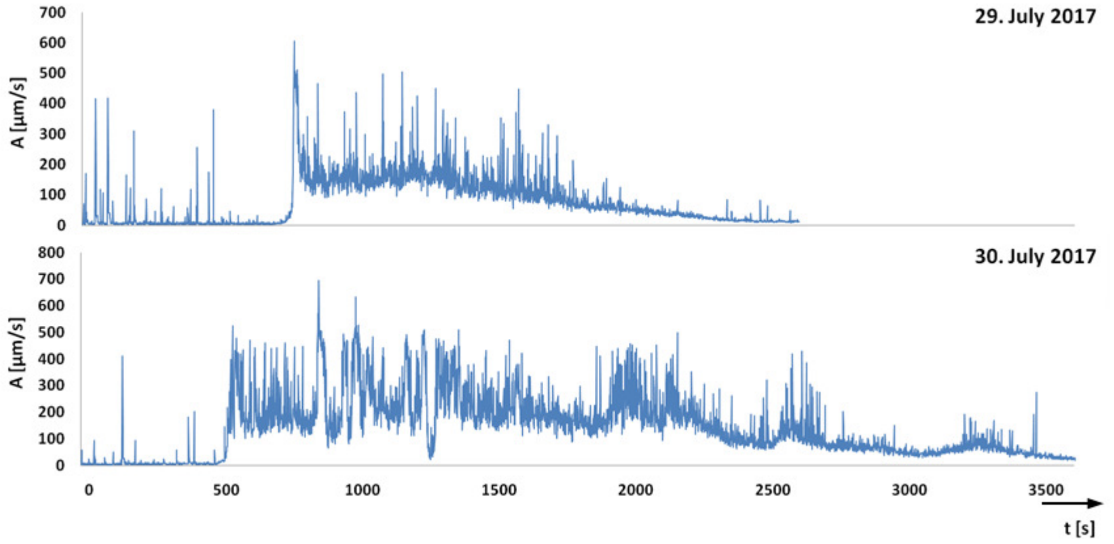

Figure A2. Seismic amplitudes of debris flows at Lattenbach (2017)

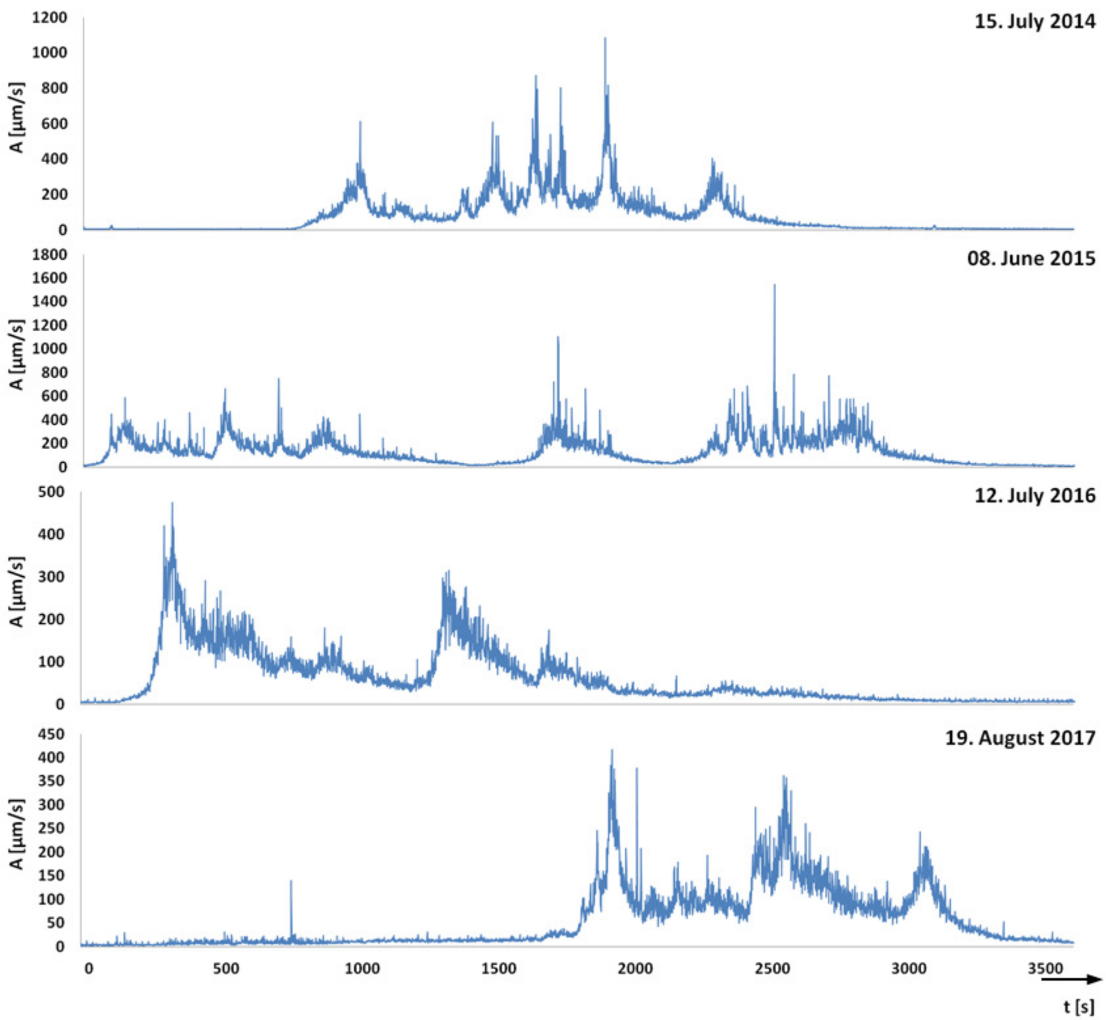

Figure A3. Seismic amplitudes of debris flows at Gadria (2014 - 2017)

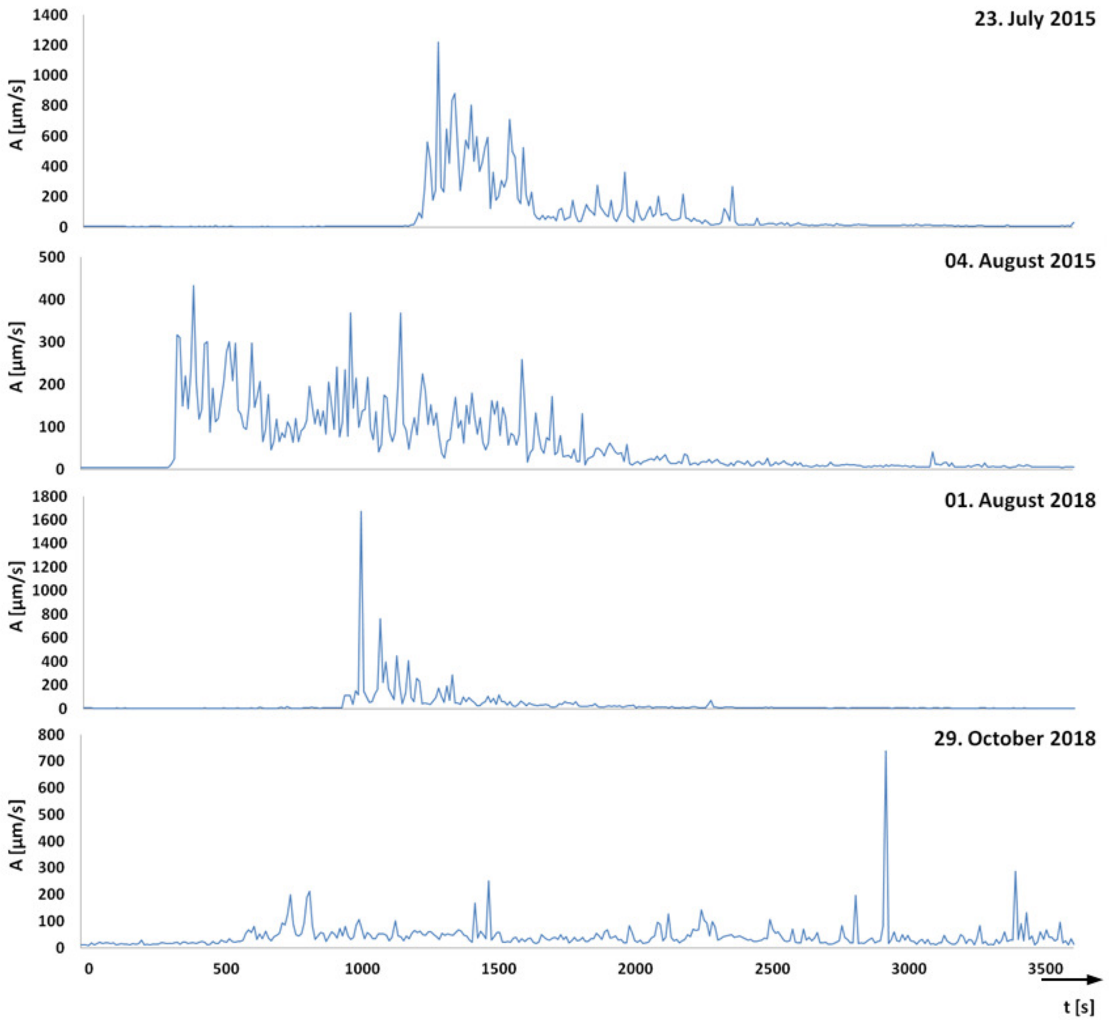

Figure A4. Seismic amplitudes of debris flows at Cancia (2015 - 2018)

Author contributions. A.S. proposed the idea and analyzed the data. V.C. contributed to the paper writing, to the figure preparation and provided data from the Gadria test site. F.C. supervised the research work. A.S. wrote the paper and all authors participated in the organization and discussion of results.

Competing interests. The authors declare no conflict of interest.

Acknowledgements. We thank Johannes Hübl (Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Vienna) for contributing data from the Lattenbach test site, Pierpaolo Macconi (Civil Protection Agency, Autonomous Province of Bozen/Bolzano) for providing data collected by the Gadria station, and Matteo Cesca (Regional Department for Land Safety, Hydrogeological Services Center, ARPA Veneto) for data relative to the Cancia site. Lorenzo Marchi, Marco Cavalli and Stefano Crema (CNR IRPI Padova) are acknowledged for debris flow volumes estimations in the Gadria basin. Andreas Schimmel was funded thanks to the research contract between ARPA Veneto and the "ACCORDO DI COLLABORAZIONE TECNICO-SCIENTIFICA ex ART. 15 DELLA L.241/90 e s.m.i. PER LA DEFINIZIONE DELLE SOGLIE DI ALLARME E LE CONSEGUENTI LOGICHE DI FUNZIONAMENTO DEL SISTEMA DI MONITORAGGIO E ALLARME DELLA COLATA DETRITICA DI CANCIA IN BORCA DI CADORE)" led by CNR-IRPI Padova in collaboration with Free University of Bozen-Bolzano and the University of Padova. Article processing charges were supported by the Free University of Bozen-Bolzano.

References

Allstadt, K. E., Lockhart, A. B., McBride, S. K., Kean, J. W., Iverson, R. M., Logan, M., Smith, J. B., Tsai, V. C. and George, D.: Overcoming barriers to progress in seismic monitoring and characterization of debris flows and lahars, in 7th International Conference on Debris-Flow Hazards Mitigation, 2019.

Arattano, M., Marchi, L.: Measurements of debris flow velocity through cross-correlation of instrumentation data, Natural Hazards and Earth System Science, Copernicus Publications on behalf of the European Geosciences Union, 5 (1), pp.137-142. hal-00299133, 2005.

Arattano, M., Marchi, L., and Cavalli, M.: Analysis of debris-flow recordings in an instrumented basin: confirmations and new findings, Natural Hazards and Earth System Science, 12, 679-686, https://doi.org/10.5194/nhess-12-679-2012, 2012

Burtin, A., Hovius, N., Turowski, J. M.: Seismic monitoring of torrential and fluvial processes, Earth Surface Dynamics, 4(2), 285-307, 2016.

CAE: Manuale del sistema di monitoraggio e allarme della colata detritica di Cancia, 9940038100T, 2014.

Cavalli, M., Crema, S., Marchi, M., Pasuto, A., Gregoretti, C., Coviello, V., Schimmel, A., Comiti, F.: Accordo di Collaborazione Tecnico-Scientifica Ex Art. 15 Della L.241/90 E S.M.I. Per la definizione delle soglie di allarme e le conseguenti logiche di funzionamento del sistema di monitoraggio e allarme della colata detritica di Cancia in Borca di Cadore.- Relazione Tecnica, 2020.

Coviello, V., Capra, L., Vázquez, R., Márquez-Ramìrez, V.H.: Seismic characterization of hyperconcentrated flows in a volcanic environment. Earth Surface Processes and Landforms, 43(10), 2219-2231. https://doi.org/10.1002/esp.4387, 2018.

Coviello, V., Arattano, M., Comiti, F., Macconi, P., Marchi, L.: Seismic characterization of debris Flows: Insights into energy radiation and implications for warning. Journal of Geophysical Research: Earth Surface, 124, 1440-1463. https://doi.org/ 10.1029/2018JF004683, 2019.

Coviello, V., Theule, J. I., Crema, S., Arattano, M., Comiti, F., Cavalli, M., Lucia, A., Macconi, P, and Marchi, L.: Combining instrumental monitoring and high-resolution topography for estimating sediment yield in a debris-flow catchment, Environmental and Engineering Geoscience, ~~in press, 2020.~~ 27(1), 95-111, 2021.

Farin, M., Tsai, V.C., Lamb, M.P. and Allstadt, K.E.: A physical model of the high-frequency seismic signal generated by debris flows. Earth Surface Processes and Landforms, 44(13), pp.2529-2543, 2019.

Gregoretti, C., Stancanelli, L.M., Bernard, M., Boreggio, M., Degetto, M., Lanzoni, S.: Relevance of erosion processes when modelling in-channel gravel debris flows for efficient hazard assessment; Journal of Hydrology, Volume 568, 2019, Pages 575-591, issn 0022-1694, https://Doi.Org/10.1016/J.Jhydrol.2018.10.001, 2019.

Havens, S., Marshall, H.-P., Johnson, J.B., Nicholson, B.: Calculating the velocity of a fast-moving snow avalanche using an infrasound array, Geophys. Res. Lett., 41, 6191-6198, doi:10.1002/2014GL061254, 2014.

Hibert, C., Malet, J.-P., Bourrier, F., Provost, F., Berger, F., Bornemann, P., Tardif, P., and Mermin, E.: Single-block rockfall dynamics inferred from seismic signal analysis, Earth Surf. Dynam., 5, 283-292, https://doi.org/10.5194/esurf-5-283-2017, 2017.

Hsu, L., Finnegan, N.J., Brodsky, E.E.: A seismic signature of river bedload transport during storm events, Geophys. Res. Lett. 2011, 38, L13407, 2011.

Hürlimann, M., Coviello, V., Bel, C., Guo, X., Berti, M., Graf, C., Hübl, J., Miyata, S., Smith, J.B. and Yin, H.Y.,; Debris-flow monitoring and warning: Review and examples. Earth-Science Reviews, 199, p.102981, 2019.

Hübl, J., Moser, M.: Risk Management in Lattenbach: a case study from Austria, Lorenzini, G., Brebbia, C.A, Emmanouloudis, D.E. (Eds.), Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows, 333-342; WIT Press, Southampton; ISBN 1-84564-169-8, 2006.

Hübl, J., Schimmel, A., Kogelnig, A., Suriñach, E., Vilajosana, I., McArdell, B.W.: A review on acoustic monitoring of debris flow, International Journal of Safety and Security Engineering, Vol. 3, No. 2, 105-115; ISSN 2041-9031 URL: http://www.witpress.com/elibrary/sse-volumes/3/2/716, 2013.

Kean, J., Coe, J., Coviello, V., Smith, J., McCoy, S. W., Arattano, M.: Estimating rates of debris flow entrainment from ground vibrations. Geophysical Research Letters, 42, 6365-6372. https://doi.org/10.1002/2015GL064811, 2015.

Koschuch, R., Jocham, P., Hübl, J.: One Year Use of High-Frequency RADAR Technology in Alpine Mass Movement Monitoring, Principles and Performance for Torrential Activities, Engineering Geology for Society and Territory, Volume 3, Edition: 1st, Chapter: 14, 69-72, 2015.

Lai, V. H., Tsai, V. C., Lamb, M. P., Ulizio, T. P., Beer, A. R.: The seismic signature of debris flows: Flow mechanics and early warning at Montecito, California. Geophysical Research Letters, 45. https://doi.org/10.1029/2018GL077683, 2018.

MAMODIS, Available online: http://mamodis.ddns.net/

Manconi, A., Picozzi, M., Coviello, V., De Santis, F., Elia, L.: Real-time detection, location, and characterization of rockslides using broadband regional seismic networks, Geophys. Res. Lett., 43, 6960-6967, doi:10.1002/2016GL069572, 2016.

Marchetti, E., Ripepe, M., Ulivieri, G. Kogelnig, A.: Infrasound array criteria for automatic detection and front velocity estimation of snow avalanches: towards a real-time early-warning system, Natural Hazards and Earth System Sciences, 15, 2545-2555, 2015.

Marchetti, E., Walter, F., Barfucci, G., Genco, R., Wenner, M., Ripepe, M., McArdell, B., Price, C.: Infrasound array analysis of debris flow activity and implication for early warning. Journal of Geophysical Research: Earth Surface, 124(2), pp.567-587, 2019.

Pérez-Guillén, C., Tsunematsu, K., Nishimura, K., and Issler, D.: Seismic location and tracking of snow avalanches and slush flows on Mt. Fuji, Japan, Earth Surf. Dynam., 7, 989-1007, https://doi.org/10.5194/esurf-7-989-2019, 2019, 2019.

Le Roy, G., Helmstetter, A., Amitrano, D., Guyoton, F. and Le Roux-mallouf, R.: Seismic analysis of the detachment and impact phases of a rockfall and application for estimating rockfall volume and free-fall height. Journal of Geophysical Research: Earth Surface, 124(11), pp.2602-2622, https://doi.org/10.1029/2019JF004999, 2019.

Simoni, A., Bernard, M., Berti, M., Boreggio, M., Lanzoni, S., Stancanelli, L. M., and Gregoretti, C.: Runoff-generated debris flows: Observation of initiation conditions and erosion-deposition dynamics along the channel at Cancia (Eastern Italian Alps). Earth Surf. Process. Landforms, https://doi.org/10.1002/esp.4981, 2020.

Schimmel, A., Hübl, J.: Automatic detection of debris flows and debris floods based on a combination of infrasound and seismic signals, Landslides Vol. 13(5), 1181–1196, ISSN 1612-510X, doi: 10.1007/s10346-015-0640-z, 2016.

Schimmel, A., Hübl, J., McArdell, B., Walter, F.: Automatic identification of alpine mass movements by a combination of seismic and infrasound sensors, Sensors, 18(5), 1658 (19 pp.), https://doi.org/10.3390/s18051658, 2018.

Takezawa, N., Yanagimachi, T., Yamakoshi, T., Tamura, K., Suwa, H., Kanno T.: Estimation of frontal velocity of debris flows by monitoring the amplification rate of seismic wave, Congress Interpraevement, 2010.

Theule, J.I., Crema, S., Marchi, L., Cavalli, M., and Comiti, F.: Exploiting LSPIV to assess debris-flow velocities in the field, Nat. Hazards Earth Syst. Sci., 18, 1-13, https://doi.org/10.5194/nhess-18-1-2018, 2018.

Ulivieri, G., Marchetti, E., Ripepe, M., Chiambretti, I., Segor, V.: Infrasonic monitoring of snow avalanches in the Alps, Proceedings International Snow Science Workshop 2012, Anchorage, Alaska, pp.723-728, 2012.

Walsh, B., Jolly, A., and Procter, J.: Seismic analysis of the 13 October 2012 Te Maari, New Zealand, lake breakout lahar: Insights into flow dynamics and the implications on mass flow monitoring, J. Volcanol. Geoth. Res., 324, 144-155, https://doi.org/10.1016/j.jvolgeores.2016.06.004, 2016.

Walter, F., Burtin, A., McArdell, B. W., Hovius, N., Weder, B., Turowski, J. M.: Testing seismic amplitude source location for fast debris-flow detection at Illgraben, Switzerland, Nat. Hazards Earth Syst. Sci., 17, 939-955, https://doi.org/10.5194/nhess-17-939-2017, 2017.

Zhang, S., Hong, Y., Yu, B.: Detecting infrasound emission of debris flow for warning purpose, 10. Congress Interpraevement, 2004.