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: Velio Coviello (velio.coviello@cnr.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 of other mitigation measures. ~~Previous~~ Debris-flow velocity can be calculated using seismic data recorded at two monitoring stations located along the channel and 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~~ discharge of each surge can be 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~~ the maximum amplitude of the seismic signal. This work ~~provide~~ provides a first approach for estimating the ~~debris flow volume and velocity based on the seismic signal~~ total volume of debris flows from the integrated seismic energy detected with simple, low-cost geophones installed along ~~the~~ a debris-flow channel. The developed methods were applied to seismic data collected ~~on~~ from 2014 to 2018 in three different test sites in the European Alps: Gadria and Cancia (Italy), and Lattenbach (Austria). An adaptable cross-correlation time window was used to calculate the velocity of the different surges, 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~~ of the inter-stations distance on velocity estimation. A ~~simple approach based on a~~ linear relationship between the squares of seismic amplitudes ~~(-~~ a proxy for seismic energy ~~) and event volumes -~~ and independent measurements of the debris-flow volume is proposed for a first order estimation the ~~latters.~~ latter. Uncertainties in the volume estimations are controlled by flow properties - such as liquid or viscous surges generating low amplitude signals and thus underestimating the calculated volume - but in most cases (9 out of 11 events of the test dataset of the Illgraben basin, CH) the order of magnitude of the debris-flow volume is correctly predicted.

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 (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. Seismic-based monitoring and warning systems have become increasingly applied worldwide to mitigate risks associated to debris flow processes. 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~~ velocity and volume.

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. 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. The estimation of the debris-flow ~~magnitude~~ volume 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~~ possible approaches 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 and~~ the local magnitude and the duration magnitude detected by broadband seismic networks. The first is computed using the maximum amplitude while the second using the total duration of the seismic train produced by the seismic source (i.e., the rockslide). 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. ~~This scaling relationship suggests that~~ Using such scaling relationships, the estimation of ~~debris-flow volumes~~ the flowing mass 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~~ a geophone and the information about flow velocity. Despite such recent advances, the estimation of debris flow 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). Remarkably, most of the (quite few) studies published so far on this topic have addressed estimations in single catchments only.

This paper ~~intends to explore~~ explores the possibility to develop a simple method to predict debris flow velocity and volume based on seismic sensors ~~, based on limited calibration data. This would enable the method to be easily applicable in different catchments, at least for first order estimations.~~ installed along the channel, with a limited calibration dataset. 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. Specifically, the proposed method is intended to be easily applicable in different catchments, at least for first order estimations of debris-flow volumes.

2 Methods

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

~~Map showing the location of the study catchment.~~

The Gadria basin is located in the Vinschgau-Venosta valley, in 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 ?? gives an overview of the catchment and the monitoring setup.~~ The geophones G1, 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 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~~ reliably detects events in real time directly at the sensor site (Schimmel and Hübl, 2016; Schimmel et al., 2018).

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

The Cancia channel is located in the Dolomites within the Province of Belluno(Italy), and the catchment features an area of 2.5 km^2 on the southwestern slope of Mount Antelao (3264 m a.s.l.). 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 volume estimation and velocity calculation are recorded by the geophones installed at station 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 volume estimation. Beside a monitoring system of the company CAE, three monitoring stations have been installed by Universities of Padova, Bologna and Bolzano in ~~2019 (Figure ??a).~~ 2019. 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., 2020).

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

Finally, the Lattenbach Creek (district of Landeck, Tyrol) has a catchment area of 5.3 km² 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 ??), and these are equipped with flow height (radar gauges), geophones, video cameras, 2D-Laser scanner. 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 m. The geophone data of these from the 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. Figure 1 gives an overview of the three catchments and the monitoring setup.
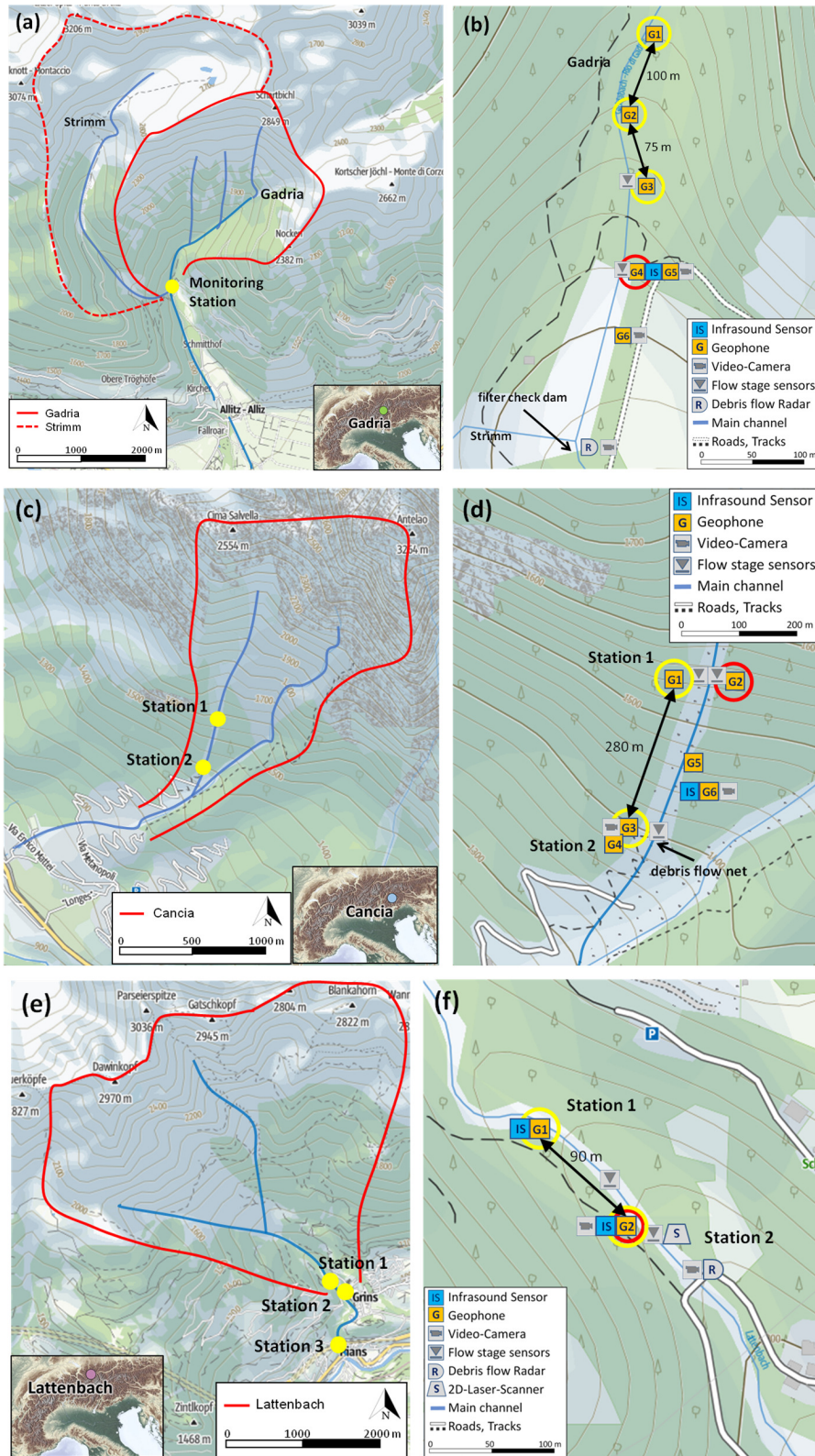
Figure 1. (a) Overview of the Gadria site (a); Cancia site (c); Lattenbach site (red line: catchment dividee); (b),(d),(f) Closer view of the monitoring stations and sensor setup(background images: ©Google Maps, 2020 (Maxar Technologies)).

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

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~~ as signal envelope (Arattano et al., 2014) from the raw data recorded at the reported sampling rates. At Cancia, an internal 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 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 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) between the two stations. 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 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 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~~ The number of samples is set equal to the distance in m, which means that a resolution from 1 ms^{-1} is possible which seems to be a phyisical meaningful starting value for describing turbulent debris flows. Three different sliding time window sizes are used because an adaptation of the time window ensures better results for the cross-correlation for all flow stages. For choosing the window length, the ratio between maximum amplitude and minimum amplitude is analysed in the starting window size which has a number of samples equal to the distance. Analyses of the seismic data of several events showed that when such ratio >6 the debris flow features an adequate signal shape for cross-correlation to be adopted. If the ratio is <6, the window
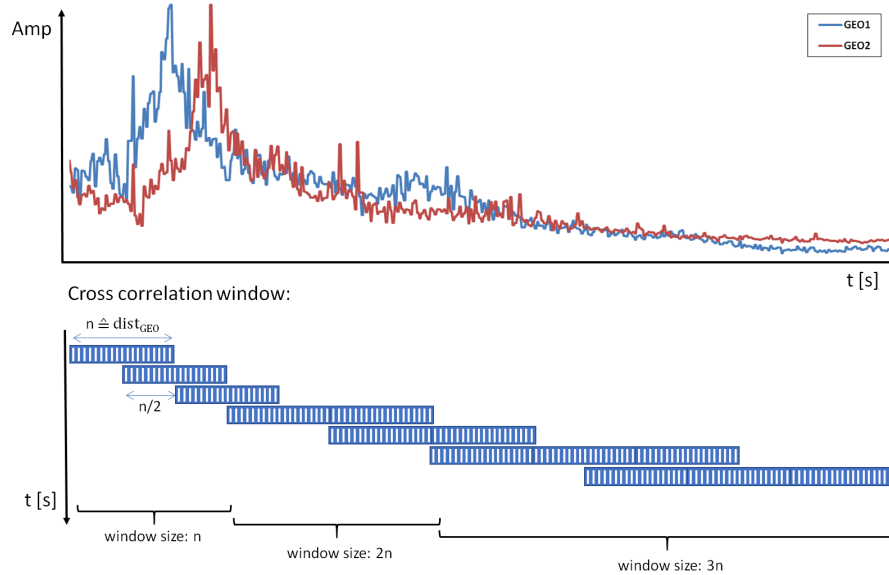
Figure 2. Methode cross-correlation analysis: window sizes and overlaps.

length will be enlarged by another number of samples equal to the distance. If the signal shape still is not suitable, the window will be further expanded. Figure 2 shows the principle of the adaptive window sizes. Therefore, the lowes velocity that can be calculated is theoretically $1 \ \mathrm{ms^{-1}}$ in the first, typically rougher part of the debris flow hydrograph, with a signal length equal the distance, and it could reduce to $0.33 \ \mathrm{ms^{-1}}$ for the smoother, tail phase of the event if a window length of three times the distance is used. Cross-correlation is performed ~~twice with a sliding window, since~~ with an overlap of ~~the half sample numbers offers most consistent results~~half of the sample numbers. The two signals are normalized in the window frame by the maximum amplitude value. Only if the cross-correlation coefficient exceeds 0.8 the result is kept for the velocity calculation. Since the cross-correlation analyses is performed at 1 s time steps, the Cancia and Gadria data are upsampled to a sample rate of 1 Hz. Therefore amplitude values from Cancia and Gadria are constant over 10 s and 2 s, respectively.

2.2 Volume estimation

As reported in the introduction, a linear trend between the seismic energy (J), which is proportional to the square of the seismic amplitude ($\mathrm{m^2 s^{-2}}$), and the kinetic energy per unit area produced by debris flows has been observed 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. 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, 2D scanners and debris flow radar) in the study basins (Schimmel et al., 2018; Coviello et al., 2021; Simoni et al., 2020). 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~~ The performances of the methods are investigated and discussed using 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

145 close to the channel (between ~~10 and 20~~ 15 and 25 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 ~~.~~ can be neglected. Also intense rainfall and wind can produce ground vibration that geophones detect. However, seismic signals recorded by sensors installed at small distance from the channel (from 15 to 25 meters, in our case) are dominated by in-channel processes. This is particularly true in our study sites, which are located in lower reaches of the main channels where the debris flow surges

150 are well formed and characterized by velocities of several meters per seconds and flow depth in the order of meters. To make data analysis comparable among the sites, the lowest sampling rate (10 s 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 s.

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 7.

	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. (2020)
	04.08.15	20000	2000	Simoni et al. (2020)
	01.08.18	4500	2700	Simoni et al. (2020)
	29.10.18	11000	3200	Simoni et al. (2020)
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

First we present the results about velocity estimation adopting the methods described above, applied to three debris flows events
recorded in different catchments. Figure 3 illustrates velocity estimations applied to the Lattenbach event occurred on ~~30.~~ 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 4 displays the seismic signals and the velocity estimation for a debris flow occurred in the Gadria on ~~08.~~ 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 of 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 5 shows the case of a debris flow in the Cancia channel. This event was recorded on ~~01.~~ 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.
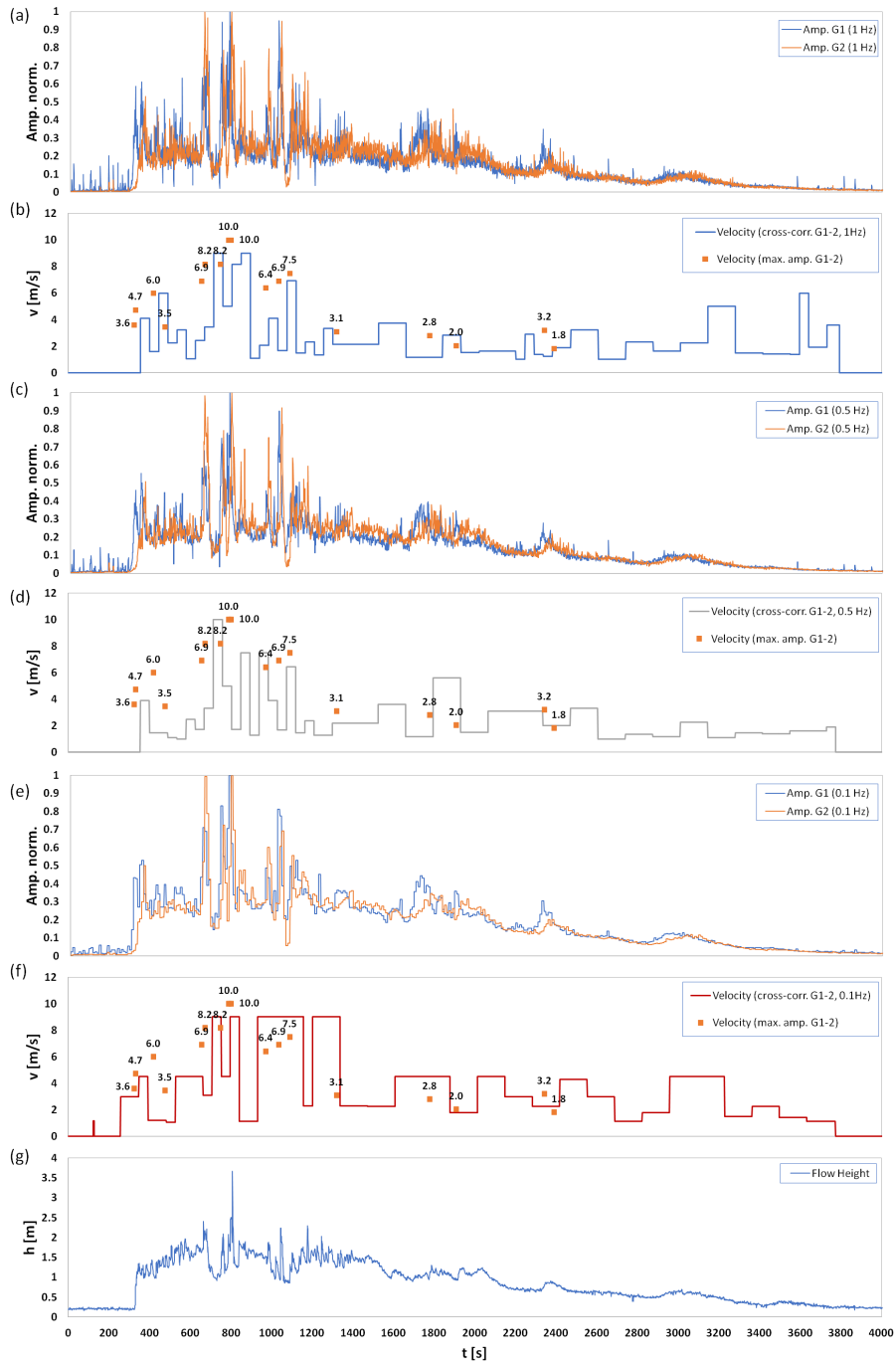
Figure 3. Debris flow at Lattenbach on ~~30.~~ 30 July 2017: (a,c,e) normalized amplitudes of the two geophones (G1,G2), (g) flow height, (b,d,e) velocity estimation based on maximum values and cross-correlation (compared for sampling rates of 1 Hz, 0.5 Hz and 0.1 Hz)
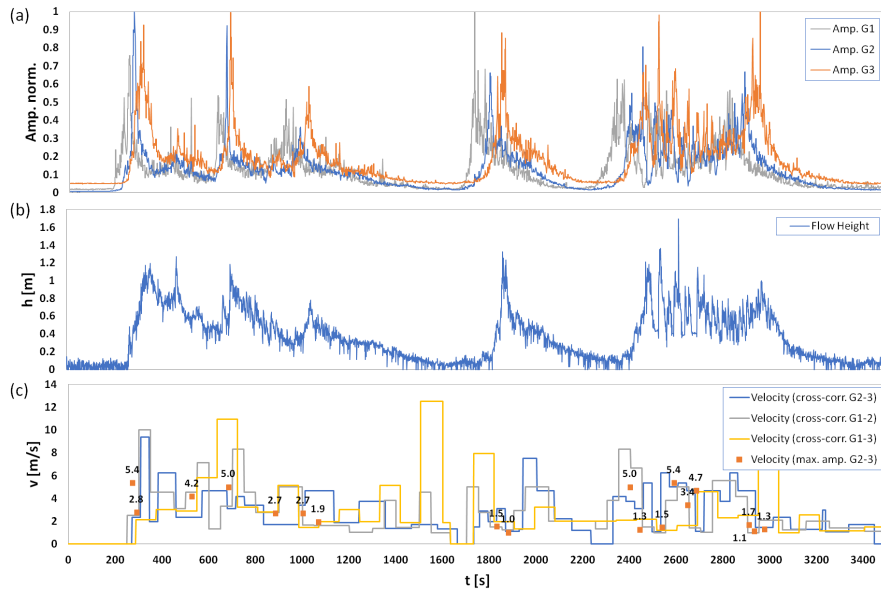
Figure 4. Debris flow at Gadria on ~~08.~~ 08 June 2015: (a) Normalized amplitudes of the three geophones (G1,G2,G3), (b) flow height, (c) velocity estimation based on maximum values and cross-correlation
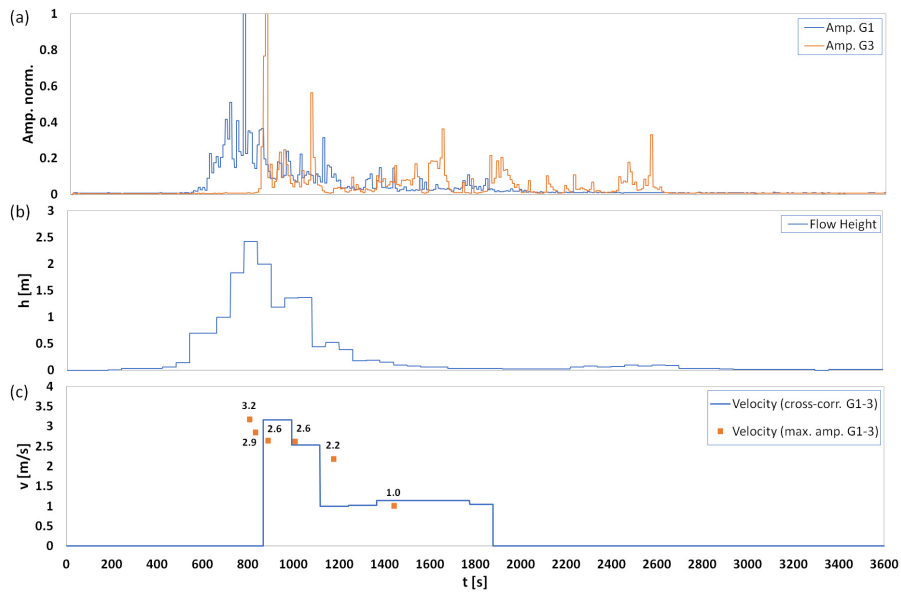
Figure 5. Debris flow at Cancia on ~~01.~~ 01 July 2020: (a) normalized amplitudes of the two geophones (G1,G3), (b) flow height, (c) velocity estimation based on maximum values and cross-correlation
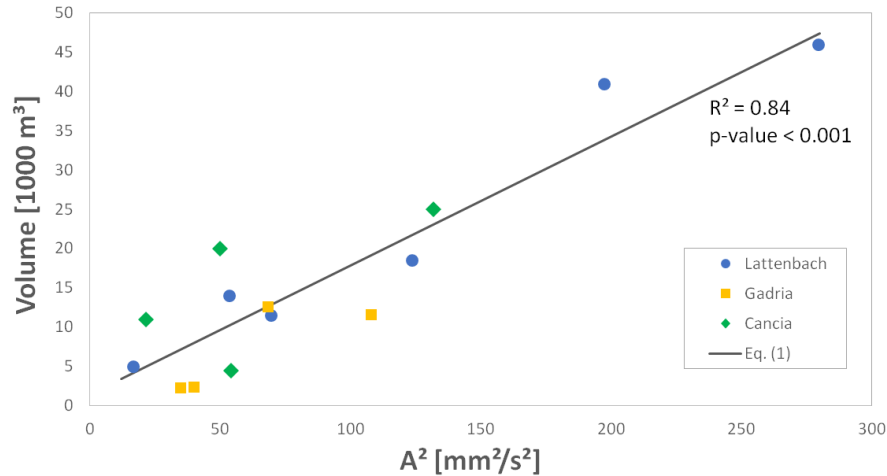
Figure 6. Relationship between squared integrated seismic amplitude and total volume based of the debris flow events listed in Table 2 (from Gadria, Lattenbach and Cancia)

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). ~~The method is tested against 11 independent debris-flow volumes recorded at Illgraben, Switzerland, from 2015 to 2017.~~ Figures 6 shows that the use of the squared seismic amplitudes (A^2 in $\mathrm{mm^2s^{-2}}$) 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:

$$V_{tot} = 164\,A^2 + 1419 \tag{1}$$

The method has then been tested against 11 independent debris-flow volumes recorded at Illgraben, Switzerland. Figure 7 compares all the observed values (vertical axis) for total volume to the predicted values (horizontal axis) according to Eq. 1. Two events at Illgraben plot ~~out~~ quite far off the confidence level shown in Figure 7. Possible reasons for the poor prediction of their volumes by Eq. 1 ~~will be~~ is provided in the discussions.
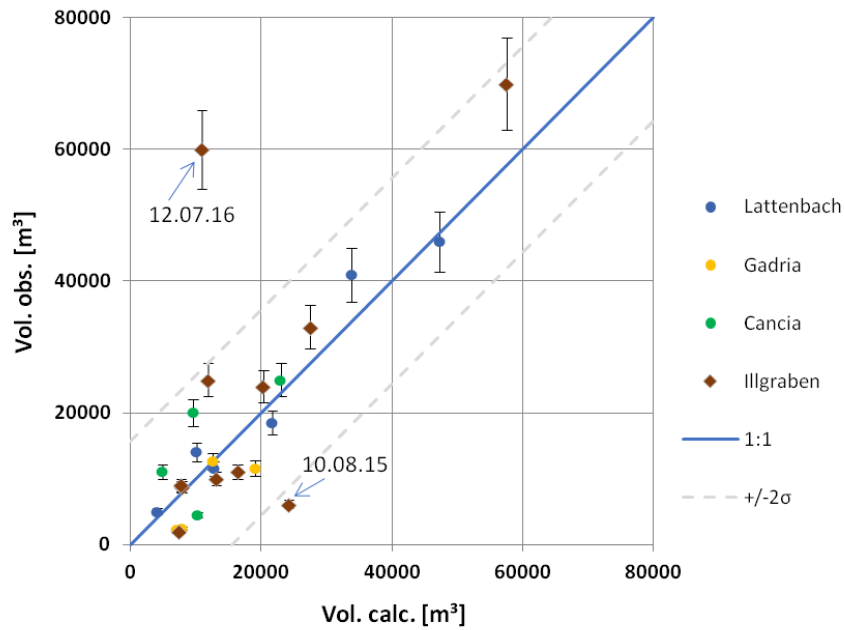
Figure 7. Comparison of the predicted volume vs observed volume. The dark blue line represents the one-to-one relationship and the dashed lines represent the confidence interval of the distribution.

4 Discussion

Arattano et al. (2012) showed that the cross-correlation technique applied on seismic signals can be an useful tool to analyze 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 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 provides solid estimates of debris-flow velocity, as temporal resolution the temporal resolution of the calculation is high during the fast, initial stages of the flow, while longer window length are applied for smoother flows, thus permitting to avoid wrong correlation results. Arattano et al. (2012) already showed how the cross-correlation technique can provide a reliable estimation of the flow velocity even when the signals recorded at the two monitored cross-sections do not present a clear, common feature, i.e., typically the passage of the debris-flow front. Nonetheless, some significant signal features are required such as a progressive rise and subsequent decrease of the signal amplitude. Signals characterized by many amplitude peaks close to each other produced, for instance, by the propagation of roll waves can represent a limitation to the application of cross-correlation methods (Figure 5c). The validation approach for the velocity estimates, i.e. manually determining matching amplitude peaks at the two stations, is also affected by uncertainty. In the Gadria, this is particularly evident for the tail of the debris flow of 08. June 2015 (Figure 4c, from t = 2400 s) during which roll waves propagate and produce multiple peaks, one following the other. The uncertainty in the manual velocity calculation was also observed in previous analysis based on data gathered with a pair of flow stage sensors and led to the approximation of lumping multiple waves into one single surge for the subsequent volume estimation (Coviello et al., 2021). The velocity estimates of surges lacking multiple peaks (i.e., from t = 200 s to 2400 s in Figure 4c) are consistent with those performed with the flow stage sensors located downstream from G3 (Figure 1c). Indeed, they are slightly higher (i.e., differences from 0.3 to 1.7 ms^{-1}) than those calculated by the flow stage data on a milder sloping channel reach (Coviello et al., 2021).

Importantly, our study benefited from three, quite different test sites. The influence of different distances between the geophones is evident on the velocity estimation. 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 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 provide a significant difference in the signals in an appropriate time, so that the cross-correlation offers 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 every 10 s is available, so that the signal shapes can be very different at the two geophones, 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 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. However, in Cancia velocities estimated on the basis of image analysis of time-lapse videos on previous events (Simoni et al., 2020) are in the same range (e.g. 1.5 to 4 ms^{-1} for a debris flow on 23. July 2015). Therefore we believe that the lower velocities in Cancia compared to Gadria and Lattenbach 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.~~ 30 July 2017 (Figure 3). 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 3 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 debris flow (Coviello et al., 2019). Alternatively, flow velocity can be measured by 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. When velocity data measured by the debris flow radar in the Lattenbach (unpublished data) are compared against values calculated from the geophones there installed, very similar results can be observed. In fact, the maximum velocity measured by the debris flow radar for the event on 30 July 2017 is 10.0 ms^{-1}, while the maximum value calculated from the geophone data is 9.0 ms^{-1}. The mean velocity of the whole event is 1.8 ms^{-1} based on the debris flow radar, and 1.9 ms^{-1} for the presented method based on the geophone data.

A linear trend between the square of the seismic amplitudes and the debris flow 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)~~ well is in agreement with the physical processes linking seismic energy to debris flow ~~mass~~parameters such as mass and velocity combined or peak discharge, as already noted by ~~Coviello et al. (2019)~~other authors (Coviello et al., 2019; Andra[...]. Figure 7 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.~~ 2017 (Table 3). This analysis suggest that it is possible to obtain first-order estimates of 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

Table 3. Errors in the volume prediction for the Illgraben test dataset.

Event date	Observed Vol. [m^{-3}]	Predicted Vol. Eq. 1 [m^{-3}]	Error Eq. 1	Predicted Vol. scaled A^2 [m^{-3}]	Error scaled A^2	Notes
22.07.15	8700	7866	10%	8167	6%	
10.08.15	6100	24208	-297%	24667	-304%	high flow velocity
14.08.15	25000	11907	52%	12247	51%	
15.08.15	2000	7503	-275%	7800	-290%	smallest event
12.07.16	10000	13148	-31%	13500	-35%	
12.07.16	60000	10933	82%	11263	81%	liquid front, viscous tail
22.07.16	11000	16414	-49%	16798	-53%	
09.08.16	9000	7739	14%	8038	11%	
29.05.17	70000	57544	18%	58324	17%	
04.06.17	24000	20344	15%	20765	13%	
14.06.17	33000	27498	17%	27988	15%	

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.~~ 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.~~ 12 July 2016 debrs flow), the velocity of the first surge was high (7.8 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 over the event duration and for an automatic volume estimation (like the method presented in Schimmel et al. (2018)) 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.

Nonetheless, adopting such a phyisically-sound empirical model, a 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 volume. Therefore, this method is still quite far from the goal of having a real time, accurate volume estimation to be implemented in early warning systems. ~~However, the method could provide a rough estimate on event volume~~ Nonetheless, a rapid estimate of the order of magnitude of the debris-flow volume would become available. Therefore, 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.

We highlight again that our methods is based on seismic data gathered in the near field, i.e. geophone stations located along the channel. For such a volume estimation, small differences in the distance sensor-channel are negligible compared to
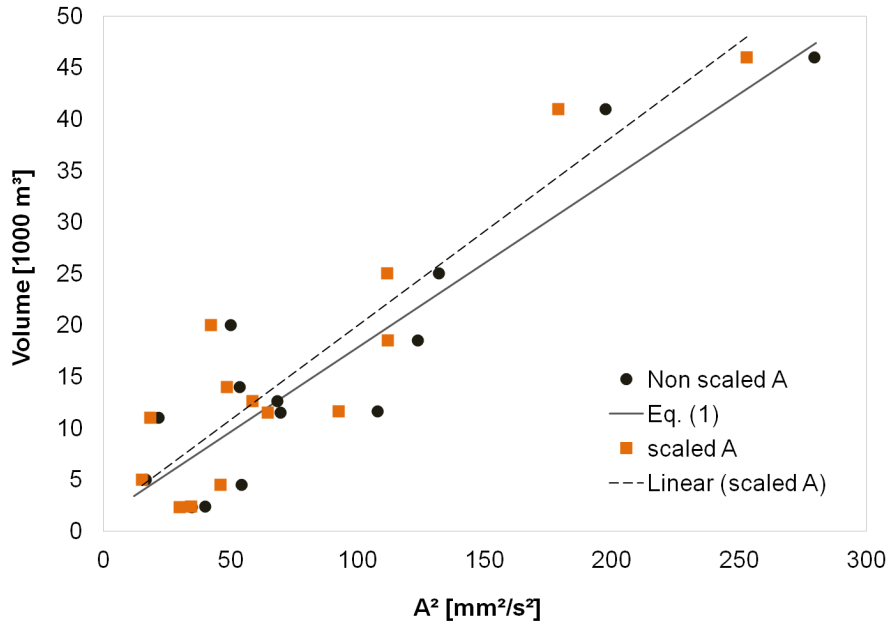
Figure 8. Comparison of the relationship between debris flow volumes vs scaled and non-scaled seismic amplitutes.

uncertainties descending from the variability of flow properties. Indeed, the distances sensor-channel for the different sites are 15 m at Lattenbach, 23 m at Gadria, 25 m at Cancia and 15 m at Illgraben. We then applied a simple empirical relation to model the decay of the seismic amplitude with distance:

$$A(d) = A\,e^{-\pi\,f\,d/Q\,v_u} \tag{2}$$

275 where d is the distance sensor-channel in m. We used a value of quality factor of $Q = 20$ suggested as a reasonable approximation for the relatively high frequencies and shallow depths of interest (Tsai et al., 2012) and a reference value for group velocity (v_u) of 1300 ms^{-1} (Coviello et al., 2019). An additional approximation was needed to apply the formula using aggregated values of amplitude recorded with different sampling rate and recording frequency (Table 1). We assumed that fronts of the different surges are the dominant sources of the seismic signal during the respective time window. This assumption is

280 consistent with our approach of calculating the mean velocity of each surge by means of the cross-correlation technique, which needs to split the entire debris-flow signal. We tested values of f ranging from 10 to 20 Hz, typical of the main frequency of debris flows. Higher differences in the scaled amplitude are obtained with the lower frequency value ($f = 20$ Hz) so we used this latter value in the calculation to maximize the uncertainties. Finally, we recalculated the debris-flow volumes using a linear regression equation similar to Eq. 1 but based on the square of the scaled amplitudes (Figure 8). Results clearly show how the

285 differences in the calculated volumes with the non-scaled and the scaled amplitude equations are negligible (Table 3).

Studies of different events also showed a large dependency of the seismic amplitudes and their frequency spectrum on the velocity of the debris flow. For example, Lai et al. (2018) ~~presents~~ proposed 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 debris flow velocity and grain size distribution can result in a more accurate calculation of debris flow volume. The influence of the sediment concentration on the seismic data can therefore improve the results of the volume estimation, but there is still no method to automatically estimate the sediment concentration on seismic data, which could be implemented in the 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 still poses ~~high~~ large uncertainties and is far 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 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 length adapted to the signal waveform improves velocity estimation over the entire debris flow duration (from fast, initial stages to smoother flows).

The estimation of the debris-flow ~~magnitude~~ volume 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 the order of magnitude of debris flow volumes can be ~~reasonably - within a +- 20% error in most cases -~~ correctly 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 volume identification usable for a warning system. In fact, ~~beside the magnitude,~~ flow velocity and the sediment concentration have also a large influence on the seismic amplitudes of a debris flow, so including them in the ~~magnitude~~ volume estimation could lead to more accurate results..

Data availability. A temporary private link to the geophone dataset gathered at Gadria and Lattenbach is provided as supplementary material to support the peer review process. In the final paper, this link will be substituted with a persistent link to an Open Access data repository (http://ds.iris.edu/ds/products/esec/).

6 ~~Events from 2014 to 2018~~

~~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.~~

~~Seismic amplitudes of debris flows at Lattenbach (2015 - 2016)~~

~~Seismic amplitudes of debris flows at Lattenbach (2017)~~

~~Seismic amplitudes of debris flows at Gadria (2014 - 2017)~~

~~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
320   provided data from the Gadria test site. F.C. supervised the research work. 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
325   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 "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
330   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.

Andrade, S.D., Almeida, S., Saltos, E.: A simple and general methodology to calibrate seismic instruments for debris flow quantification: application to Cotopaxi and Tungurahua volcanoes (Ecuador). Landslides 19, 747-759 (2022). https://doi.org/10.1007/s10346-021-01784-5, 2022.

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

Arattano, M., Abancó, C., Coviello, V., Hürlimann, M.: Processing the ground vibration signal produced by debris flows: The methods of amplitude and impulses compared. Computers and Geosciences, 73,17-27. https://doi.org/10.1016/j.cageo.2014.08.005, 2014.

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, 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.

370 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-

375 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,

380 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 broad-

385 band 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.

390 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.

395 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.

400 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

405 Earth Syst. Sci., 18, 1-13, https://doi.org/10.5194/nhess-18-1-2018, 2018.

Tsai, V. C., Minchew, B., Lamb, M. P., Ampuero, J.P.: A physical model for seismic noise generation from sediment transport in rivers. Geophysical Research Letters, 39, L02404. https://doi.org/10.1029/2011GL050255, 2012.

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.

410 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.

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