Debris-flow detection for early warning purposes: recent advances, open problems, and future challenges

Velio Coviello[1*]

[1]Research Institute for Geo-Hydrological Protection (IRPI), National Research Council (CNR), Padova, Italy

Abstract. The mitigation of risk caused by debris flows is increasingly pursued by means of non-structural measures, including early warning systems (EWSs). Nowadays, EWSs are becoming attractive thanks to their flexibility and due to the new paradigm of smart sensor networks, proposed as a tool to monitor and gather intelligence from the surrounding environment. Also, an increasing number of extreme meteorological events is expected due to climatic changes, resulting in a consequent growing risk in areas considered safe so far. Although the technological development of detection systems based on low-cost sensor networks has recently spurred a great deal of interest, very few success stories exist of EWSs operational for long periods and trusted by local authorities. In this work, I present an overview on the recent advances, open problems, and future challenges in the field of detection of debris flows for early warning purposes, with a special attention to the European Alps. I discuss (i) the uncertainties related to the use of rainfall thresholds and their possible improvement based on field observations in the source areas, (ii) the new opportunities that seismo-acoustic sensors open in terms of warning performances and lead time, (iii) the problematic interaction of EWSs with structural mitigation measures, and (iv) the old but still actual problem of responsibility in issuing an alarm. Finally, I debate the "information paradox" that can contribute limiting the adoption of EWSs in future and the possible benefits of communication and dissemination.

1 Introduction

Debris flows are among the most dangerous natural hazards that threaten people and infrastructures in the Alpine region due to their rapid motion and transport capacity [1]. Starting from the 1960s, many efforts and investments have been devoted to build channel control structures such as check-dams and retention basins all over the Alps. However, such structures are expensive to build and to maintain because trapped sediments must be periodically removed. In addition, in narrow Alpine valleys there is not always enough space for constructing new channel control structures, which also have a negative impact on mountain landscapes. The current climatic change represents a further challenge for the design of new mitigation measures. In the near future, prolonged heat waves and extreme rainfall events will likely increase both the intensity and the frequency of debris flows.

Non-structural mitigation measures can considerably decrease the impact of debris flows [2]. Long-term datasets collected in catchments characterized by recurrent debris-flow activity (i.e., at least 1-2 events per year) are essential to improve hazard maps, to validate the outcome of debris-flow models and to design early warning systems (EWSs). A growing number of scientists and local authorities are dealing with the instrumental detection of debris flows with distributed sensor networks. In particular, compact and low-cost seismo-acoustic sensors represent a unique opportunity to gather a continuous stream of data representative of the different processes occurring in the basin. In this work, I present an overview on the recent advances, open problems, and future challenges in the field of detection of debris flows for early warning purposes.

2 EWSs for debris flows

Rainfall thresholds may have practical applications in the determination of risk levels for shallow landslides and debris flows at regional scale [3]. However, rainfall thresholds are affected by significant uncertainty due to the spatial variability of the rainfall field and because of the heterogeneities in geology, climate, and land use that characterizes mountain catchments [4]. Therefore, EWSs based on rainfall thresholds may produce a large number of false alarms and they still do not meet the performance level required for effective applications at the single catchment scale (Figure 1).

Operational EWSs are often based on the instrumental detection of the debris flow upstream of a defined vulnerable site [2]. These EWSs typically consist in sensors deployed within the channel (flow stage sensors and video cameras) detecting the flow passage directly, or on sensors deployed nearby the channel (seismic and infrasound sensors) able to detect the flow remotely through its elastic energy radiation in the ground and in the atmosphere. They have a much smaller lead time than systems based on rainfall thresholds but can be very

* Corresponding author: velio.coviello@cnr.it

effective in terms of detection rate (Figure 1). EWSs making use of in-channel sensors are highly reliable but typically require strong efforts for installation and maintenance and in most of the cases result in a very short lead time. EWSs based on seismo-acoustic sensors permit to extend lead time by detecting the flow higher up in the channel [5], [6]. Most of them adopt geophones or the combination of a single geophone and an infrasound microphone nearby the channel [7], [8]. Seismo-acoustic techniques can be very useful for risk management, not only because they provide an early detection of the debris flow but also allow estimating its magnitude [8], [9]. Pulse doppler radars are employed to measure the flow velocity and detect intense rainfall but their diffusion is limited as they require high computing power and large storage capacity [2], [10].

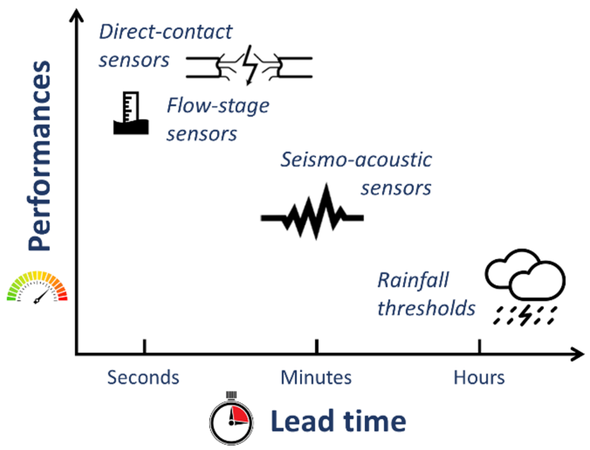

Fig. 1. Performances vs lead time of the most commonly sensors employed in EWSs. I refer to the detection of a single event, i.e. the main front. In case of secondary waves, the performances of direct-contact sensors dramatically reduce.

Despite the recent advancements and the growing interest on non-structural mitigation measures among partitioners and local authorities, very few success stories exist of EWSs operational for long periods and trusted by local authorities. In most cases, contact sensors such as trip wires and pendulum are employed (Table 1). This choice is consistent with the old rule "simpler is better" but it also descends from the need of the non-specialist decision maker to see (and show) that something solid is controlling the EWS [11]. In some cases, operational EWSs are based on both the monitoring of meteorological parameters, typically rainfall, and the detection of the debris flows after they have started by means of geophones, flow stage sensors, and video cameras. However, in most cases the element at risk to protect is a linear infrastructure such as a road or a railway crossing the torrent, thus the alarm is based on the information provided by contact sensors and geophones are employed (Table 1). This highlight how most local authorities do not like the uncertainties that are typical of critical rainfall thresholds and prefer to manage a shorter lead time but a lower number of false alarms (Figure 1). Progressive levels of alert – corresponding to different actions to take – have been proposed to make the uncertainties of rainfall thresholds acceptable [12]. However, the definitive closure of a linear infrastructure is always decided – at the best of my knowledge – when the debris flow is detected by a sensor network installed along the channel.

Table 1. Operational EWSs for debris flows in Italy, France, Switzerland, and Austria. C contact sensors, R rain gauges, H flow-stage sensors, G geophones, F infrasound sensors, V videocameras, D pulse doppler radar.

Torrent	**Element at risk**	**Sensors**	**Reference**
Rovina di Cancia (BL), IT	Road, houses	C, R, H, G, V	[12]
Rotwandbach (BZ), IT	Road	C, G	[11]
Rabbia (BS), IT	Road	C, R, V	Pasquini, 2018
Grissiano (BZ), IT	Road, houses	R, H, S, V	[13]
Rochefort (AO), IT	Road	G, V	[14]
Bouvaz (AO), IT	Road	C, V	[14]
Pont du Teu (AO), IT	Road	C, V	[14]
Baudier (AO), IT	Road	C, V	[14]
Regoud (AO), IT	Road	C, V	[14]
Berruard (AO), IT	Road	C, V	Segor, per.com.
Bellet (AO), IT	Road	C, V	Segor, per.com.
Claret, FR	Road, Railway	C, V	[15]
Saint-Martin, FR	Road, Railway	C, V	[15]
Saint-Julien, FR	Road, Railway	C, V	[15]
Boscodon, FR	Road	C	[15]
Merdaret, FR	Road	C	[15]
Arbonne, FR	Road, Railway	C, H	[15]
La Ravoire, FR	Road, Railway	C	[15]
Nant de l'Armancette, FR	Road, houses	C	[15]
Abéous, FR	Road, houses	C	[15]
Riou Sec, FR	Road, houses	C	[15]
Bondasca, CH	Road	C, R, V	[16]
Carrerabach, CH	Railway	H, V	[17]
Rotgraben, AT	Railway	G, F, V	[18]
Kühgraben, AT	Railway	G, F, V	[18]
Rosensteinergraben, AT	Road	D, V	Koschuch, per.com.
Masonbach, AT	Railway	D, V	Koschuch, per.com.
Kaunertal, AT	Road	D, V	Koschuch, per.com.

A possible improvement of rainfall thresholds can be achieved by means of observations collected in the debris-flow source areas with other instruments. Recently, the analysis of geophone data and video recordings show that different natural sources of ground vibration can be automatically classified and the hydrologic response to rainfall events in the initiation area of the catchment can be used to improve the warning performances of rainfall thresholds [19].

3 Seismo-acoustic detection

Passive, seismo-acoustic techniques are attractive because they can provide monitoring data at a safe distance from the active channel. In particular, sensors such as geophones and microphones represent a unique opportunity to monitor large areas with a dense and low-cost sensor network. On the other hand, instrument installation, maintenance and data analysis require efforts and skills in signal processing. Consequently, the employment of seismo-acoustic sensors is experiencing a growing interest among scientists but local authorities still hesitate to adopt them in operational EWSs.
There are three approaches that have been proposed for the seismo-acoustic detection of debris flows:

1. linear array of geophones,
2. network of seismometers,
3. array of infrasound sensors.

A linear array of geophones installed along a debris-flow channel was proposed as a possible tool for early warning in the Moscardo basin [20]. Geophone data demonstrated that the debris flow can be identified by analysing the variability of signal amplitude. Recently, this approach was further developed in the Gadria basin, where an automatic algorithm based on the short-time average over long-time average ratio (STA/LTA) of the seismic signal was used to early detect a debris flow in a continuous stream of seismic data and to filter out different seismic sources [7]. In general, a linear array of geophones is effective in protecting specific vulnerable sites located on the alluvial fan. Greater the distance array – vulnerable site, greater the lead time.
Seismometer commonly employed for tectonic and volcano monitoring also detect signals produced by lahars [21], [22]. Arrival-time methods leveraging data gathered at multiple stations have been used for tracking seismic sources produced by debris flows at the basin scale [6]. Recently, machine learning algorithms have been proposed to identify initial sediment mobilization and extend warning times at Illgraben, Switzerland, but their application in other locations is still limited due to the need of training datasets collected by a dense network of seismometers [23].
Low-frequency sound monitoring, typically in the infrasound (<20 Hz) band, is an emerging technique for debris-flow detection. Array of infrasound sensors and microphones can be installed at hundreds meters from the trajectories of debris flows [5]. Also, the combination of a low-cost microphone with a geophone installed at few meters from the active channel has been proposed as a compact and single-station solution for debris-flow detection [8].

4 Structural measures vs EWSs

EWSs are often considered as an alternative – also less impacting on landscape – to expensive structural mitigation measures. Actually, the choice of the mitigation measures to realize is often related to social parameters such as composition of the local community and their education to risk. As the extreme case of Cancia teaches, the relocation of settlements is hardly acceptable even if they fall into the debris-flow path [12]. On one hand, filter check dams can attenuate the severity of debris flows by reducing the flow velocity and retaining part of the volume before it reaches the areas at risk but, on the other, they alter the natural sediment transfer and require regular maintenance. In addition, the positive effects in terms of hazards reduction could be not sufficient in case of extreme rainfall events causing the debris flow to exceed the magnitude of the design event. This is particularly relevant in Alpine valleys hosting multiple debris flow channels that can be activated by the very same meteorological event. Therefore, warning systems would help manage the residual risk that results from the decrease of effectiveness of structural measures. Even when the performance of structural measures is satisfactory, EWSs can contribute to risk management by providing real-time data on the evolution of the processes and on the structural response of critical structures like debris-flow breakers. EWSs could suitably integrate structural mitigation measures in many cases but in many cases the fragmentation of competences and responsibilities among local and regional authorities do not contribute to their diffusion.

5 The "information paradox"

The knowledge of debris-flow processes and the development of automatic detection systems are sufficiently advanced to justify EWSs to be operational in many real cases. Most limitations to the large-scale adoption of such systems are due to the "responsibility issue". Who is responsible for issuing the alarm when a possible debris flow is detected? How many false alarms are acceptable, and which is the minimum lead time required for a specific infrastructure? Which actions and communication strategies correspond to the different, possible alert levels? From the (many) possible answers to these questions descend what I call the "information paradox". The information gathered with sophisticated detection systems (i.e., seismo-acoustic detection) might be considered a problem instead of an opportunity by decision makers if end-users are not informed about debris-flow risk and they are not involved in the implementation of warning protocols. This can also produce negative feedbacks in terms of more demand for structural protection measures from the local communities and thus more constructions in future (i.e., kind of levee effect), even though new constructions in high-risk areas are not recommended.
How to deal with that? More efforts in communication, dissemination, and promotion of the model of "shared responsibility" from the scientific community would surely help. This can also be considered a political

priority for the near future given the urgent need of saving space and resources in the Alpine region and the expected growing debris-flow risk in areas considered safe so far due to the increasing impact of extreme meteorological events produced by climatic changes.

Acknowledgements. I thank many colleagues for the fruitful discussions and for providing precious information about operational EWSs: Massimo Arattano, Matteo Berti, Marco Cavalli, Francesco Comiti, Sandro Gius, Marcel Hürlimann, Richard Koschuch, Pierpaolo Macconi, Lorenzo Marchi, Guillaume Piton, Andreas Schimmel, Valerio Segor.

References

[1] M. Jakob and O. Hungr, *Debris-flow hazards and related phenomena*. Springer Berlin Heidelberg, 2005.

[2] M. Hürlimann *et al.*, "Debris-flow monitoring and warning: Review and examples," *Earth-Science Rev.*, vol. 199, no. December, p. 102981, 2019, doi: 10.1016/j.earscirev.2019.102981.

[3] M. T. Brunetti, S. Peruccacci, M. Rossi, S. Luciani, D. Valigi, and F. Guzzetti, "Rainfall thresholds for the possible occurrence of landslides in Italy," *Nat. Hazards Earth Syst. Sci.*, vol. 10, no. 3, pp. 447–458, 2010, doi: 10.5194/nhess-10-447-2010.

[4] M. Berti, M. Bernard, A. Simoni, and C. Gregoretti, "Physical interpretation of rainfall thresholds for runoff-generated debris flows," *J. Geophys. Res. Earth Surf.*, pp. 1–25, 2020, doi: 10.1029/2019JF005513.

[5] E. Marchetti *et al.*, "Infrasound Array Analysis of Debris Flow Activity and Implication for Early Warning," *J. Geophys. Res. Earth Surf.*, pp. 567–587, 2019, doi: 10.1029/2018JF004785.

[6] F. Walter, A. Burtin, B. W. McArdell, N. Hovius, B. Weder, and J. M. Turowski, "Testing seismic amplitude source location for fast debris-flow detection at Illgraben, Switzerland," *Nat. Hazards Earth Syst. Sci.*, vol. 17, no. 6, pp. 939–955, 2017, doi: 10.5194/nhess-17-939-2017.

[7] V. Coviello, M. Arattano, F. Comiti, P. Macconi, and L. Marchi, "Seismic characterization of debris flows: insights into energy radiation and implications for warning," *J. Geophys. Res. Earth Surf.*, vol. 124, no. 6, pp. 1440–1463, 2019, doi: 10.1029/2018jf004683.

[8] A. Schimmel, J. Hübl, B. W. McArdell, and F. Walter, "Automatic identification of alpine mass movements by a combination of seismic and infrasound sensors," *Sensors (Switzerland)*, vol. 18, no. 5, pp. 1–19, 2018, doi: 10.3390/s18051658.

[9] A. Schimmel, V. Coviello, and F. Comiti, "Debris-flow velocity and volume estimations based on seismic data," *Nat. Hazards Earth Syst. Sci.*, vol. 22, pp. 1955–1968, 2022.

[10] R. Koschuch, P. Jocham, and J. Hübl, "One Year Use of High-Frequency RADAR Technology in Alpine Mass Movement Monitoring: Principles and Performance for Torrential Activities," in *Engineering Geology for Society and Territory - Volume 3*, 2015, pp. 69–72.

[11] V. Coviello, S. Gius, G.-F. Rufinatscha, P. Macconi, and F. Comiti, "Recent advances on debris flow early warning and risk management in Alto Adige/ South Tyrol, Italy," in *14th Congress INTERPRAEVENT*, 2021, pp. 302–304.

[12] M. Cavalli *et al.*, "Accordo di Collaborazione Tecnico-Scientifica - Relazione tecnica," 2020.

[13] V. Mair, "Il sistema di monitoraggio delle colate detritiche del Rio di Grissiano, Nalles (BZ) – oltre 10 anni di esperienza," 2019.

[14] V. Segor, "Difesa strutturale vs sistemi di detezione di fenomeni di colata detritica /valanghe: alcuni esempi in Valle d'Aosta," 2019.

[15] Y. Queffféléan, "Adéquation des services à disposition avec les besoins locaux," 2020.

[16] Geopraevent, "Debris flow alarm system Carrera creek," *www.geopraevent.ch*, 2019. https://www.geopraevent.ch/project/debris-flow-alarm-system-carrera-river/?lang=en.

[17] Geopraevent, "Rock avalanche and debris flow alarm system Bondo," *www.geopraevent.ch*, 2018. https://www.geopraevent.ch/project/rockfall-and-debris-flow-monitoring-bondoval-bondasca/?lang=en.

[18] A. Schimmel, "MAss MOvement Detection and Identification System," *http://mamodis.ddns.net/index.html*. .

[19] E. Ioriatti, "Study of debris-flow initiation through the analysis of seismic signals," Free University of Bozen-Bolzano, 2021.

[20] M. Arattano and L. Marchi, "Systems and Sensors for Debris-flow Monitoring and Warning," *Sensors*, vol. 8, pp. 2436–2452, 2008, doi: 10.3390/s8042436.

[21] H. Kumagai, P. Palacios, T. Maeda, D. B. Castillo, and M. Nakano, "Seismic tracking of lahars using tremor signals," *J. Volcanol. Geotherm. Res.*, vol. 183, no. 1–2, pp. 112–121, 2009, doi: 10.1016/j.jvolgeores.2009.03.010.

[22] B. Walsh, V. Coviello, L. Capra, J. Procter, and V. Márquez-Ramirez, "Insights Into the Internal Dynamics of Natural Lahars From Analysis of 3-Component Broadband Seismic Signals at Volcán de Colima, Mexico," *Front. Earth Sci.*, vol. 8, no. December, pp. 1–10, 2020, doi: 10.3389/feart.2020.542116.

[23] M. Chmiel, F. Walter, M. Wenner, Z. Zhang, B. W. McArdell, and C. Hibert, "Machine Learning Improves Debris Flow Warning," *Geophys. Res. Lett.*, vol. 48, no. 3, pp. 1–11, 2021, doi: 10.1029/2020GL090874.