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When instrument location makes the difference on rainfall thresholds definition: lessons learned at Cancia, Dolomites

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Abstract. Since debris flows represent one of the most dangerous natural hazard in mountain areas, Early Warning Systems (EWSs) play a crucial role in reducing the risk of these hazardous processes. Robust event pre-alert usually relies on long time series of local rainfall measures. Oftentimes regional rain gauge networks present an insufficient spatial density to grasp the highly variable spatio-temporal dynamics of debris-flow triggering events and thus relying on such networks for developing rainfall thresholds might lead to relatively low rainfall estimates. The present paper reports the development of operational rainfall thresholds for the Cancia EWS, Dolomites (NE Italy). The instrumentation configuration led to the derivation and implementation of a set of rainfall thresholds that significantly enhanced pre-alarm reliability thanks to an optimal spatial distribution of multiple rain gauges within the catchment. Notwithstanding the small number of debris flows occurred during the calibration period, rainfall thresholds were derived considering the whole population of rainfall events showcasing the statistical properties of those events that led to debris-flow initiation. Finally, the validation period served as proof of work for the proposed thresholds with no raised false alarms and with the identification of few minor, but correctly detected, debris flows.

1 Introduction

When dealing with risk management and governance in mountain environments, debris-flow Early Warning Systems (EWSs) can be regarded as one of the most effective non-structural risk mitigation measures available to the authorities [1, 2].

Amongst the most dangerous natural hazards over the Alpine region, debris flows undoubtedly get a prime role due to their destructive power and their impact on anthropic environment. When debris-flow EWSs are located in densely populated or touristic areas, their reliability must be carefully validated through the years also considering potential variations of the boundary conditions such as triggering rainfall input variability, sediment availability and channel morphology.

In the Dolomites (NE Italy) the most common debris-flow initiation process is channel bed failure/erosion due to excess runoff related to intense summer convective events [3]. Oftentimes in such areas, rainfall spatial variability manifests severe and localized gradients that can't be grabbed by the density of a typical regional rain gauge network [4, 5] and this in turn indicates the need for accurate and distributed rainfall measures within the EWS-instrumented catchment. In the present work, we summarize the EWS upgrade carried out at Cancia (Dolomites) as a scientific cooperation between regional authorities and research institutions with a peculiar focus on the rainfall threshold derivation approach for an improved alarm reliability thanks to an optimal spatial distribution of rain gauges within the catchment.

2 Study area, data and requirements

The "Rovina di Cancia" debris-flow catchment (total drainage area 2.04 km^2, area at the debris-flow formation site: 0.65 km^2, see Fig. 1) is located in a typical dolomitic context where debris flows are triggered by intense rainfall at the interface between vertical cliffs and scree slopes or on steep channels that entrenches the scree.

The study area is known for its frequent debris flows and the related hazard is enhanced by the missing connection of the Cancia channel to the receiving Boite Torrent. The debris-flow channel in fact ends with a retention basin just upstream the Cancia village. In case the retention capacity of the system is exceeded, the event can seriously damage a vast area putting in danger tens of lives [6]. Civil protection measures in conjunction with a monitoring and Early Warning

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system (EWS) have been installed by provincial authorities to mitigate debris-flow impact.

The EWS operational since 2014 was structured as follows (Fig. 1):

- station 1, 2267 m a.s.l. (close to the debris-flow triggering area), 2 rain gauges
- station 2, 1690 m, 2 level sensors, 2 geophones, 1 rain gauge
- station 3, 1525 m, 2 geophones, 2 trip wires
- station 4, 1280 m, 2 geophones, 2 level sensors, 2 trip wires
- station 5, 1080 m , 2 trip wires, 4 level sensors, traffic light on road/bridge and sirens
- station 6, in the village, traffic lights and sirens.

Data recorded by a rain gauge belonging to the regional hydrometeorological network located in the lower part of the catchment (Rovina Bassa, 1335 m a.s.l, Fig. 1) were also analyzed.

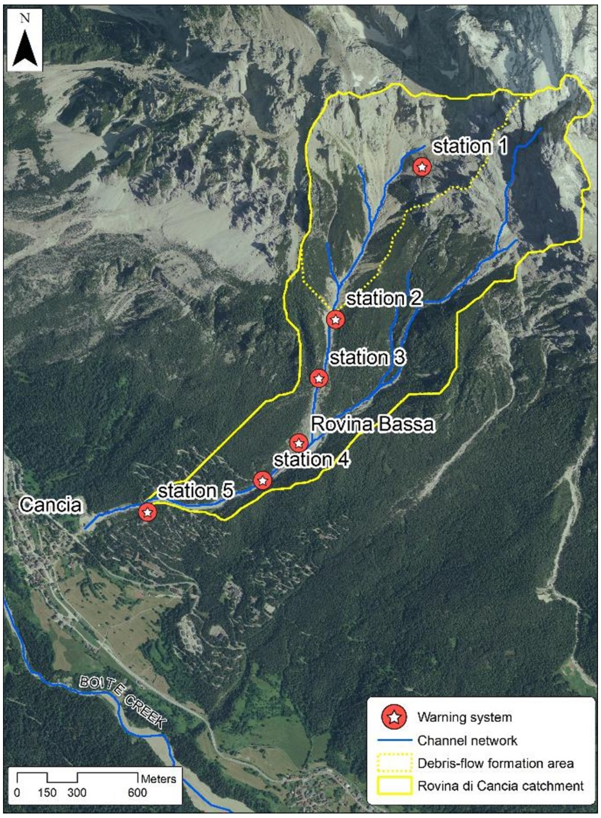

Fig. 1. Study area and location of monitoring and early warning stations.

All the stations are radio-linked to the main logic system that is available to the authorities. Leveraging the availability of monitoring instrumentation and thanks to the occurrence of several debris flows from the 2014 system installation up to 2019, the comprehensive aim of the EWS was to produce robust thresholds on rainfall, seismic and flow-level data. Such thresholds were intended to become operational as an update of the EWS working procedures that were previously relying on the regional rain gauge network instruments.

In the present paper, seismic and flow-level analyses remain in the background in respect to the main focus of the work that wants to tackle rainfall variability and rainfall thresholds performance while focusing on the pre-event warning phase.

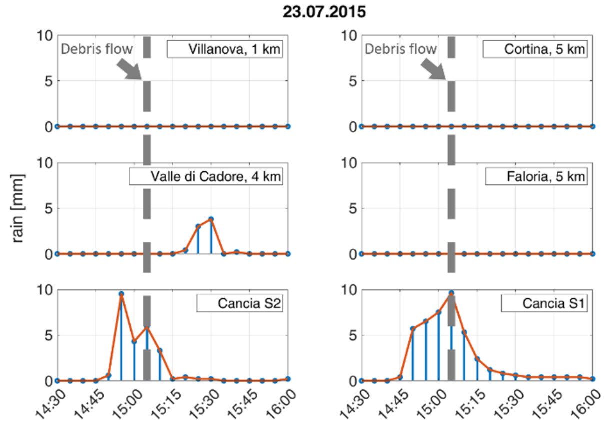

Fig. 2. Example of event rainfall representativeness for stations inside (S1 and S2) and close by the catchment (distance in km is reported within the graph). Debris-flow timing as retrieved by the trip wire activation is also indicated.

In particular, the rainfall thresholds derived in the present work take advantage of the availability of three rain gauge stations inside the catchment. The spatial variability of convective rainfall events can indeed lead to ineffective thresholds when relying on rainfall estimates computed just outside the catchment or far from the debris-flow triggering location (Fig. 2) as already observed in previous studies investigating a wider dolomitic area [3].

3 Events characterization and thresholds definition

During the period 2014-2019, four major debris flows were available for the development of rainfall thresholds (Tab.1).

Table 1. Date and volume estimation of the four major considered events for the calibration period. Volume estimation is derived by [7]

Date	Volume (m^3)
23.07.2015	25000
04.08.2015	20000
01.08.2018	4500
29.10.2018	11000

The last 2018 event represents the well-known Vaia storm [8] that hit north-eastern Italy with prolonged intense rainfall and whose temporal pattern is quite different from the typical very intense and rapid summer storms that usually trigger debris flows in the study area.

In addition, two minor events were also partially recorded by the system or by local witnesses, but they did not reach the retention basin. Major events were indeed considered with particular attention since they represent the conditions capable of stressing the whole system even if with different degrees of severity.

In the present work, we are not trying to correlate the event magnitude with the rainfall volume, rather we're seeking an event threshold that might trigger a significant response at the catchment scale thus standing on the safe side of the estimate and at the same time relying on similar recorded events that stressed the whole system.

To rely on a large testing dataset, it was decided not to consider only the few rainfall events that triggered debris flows, but rather to leverage the present rain gauge configuration in a different way. All rainfall events were thus automatically detected using a minimum accumulation threshold of 1 mm and a hiatus of 6 hours for separating two consecutive events. Such values are considered appropriate for the test site (and coherent with similar alpine catchment applications, generating a quite stable number of events [9, 10 and references therein] and bearing in mind also that the debris-flow formation catchment is vastly covered by thick and highly permeable loose debris with no evident permanent runoff.

Doing so, we obtained more than 800 events per station (within the working period of the EWS that usually covers the range between late spring and early autumn), and we tried to seek helpful information inside such a numerous dataset.

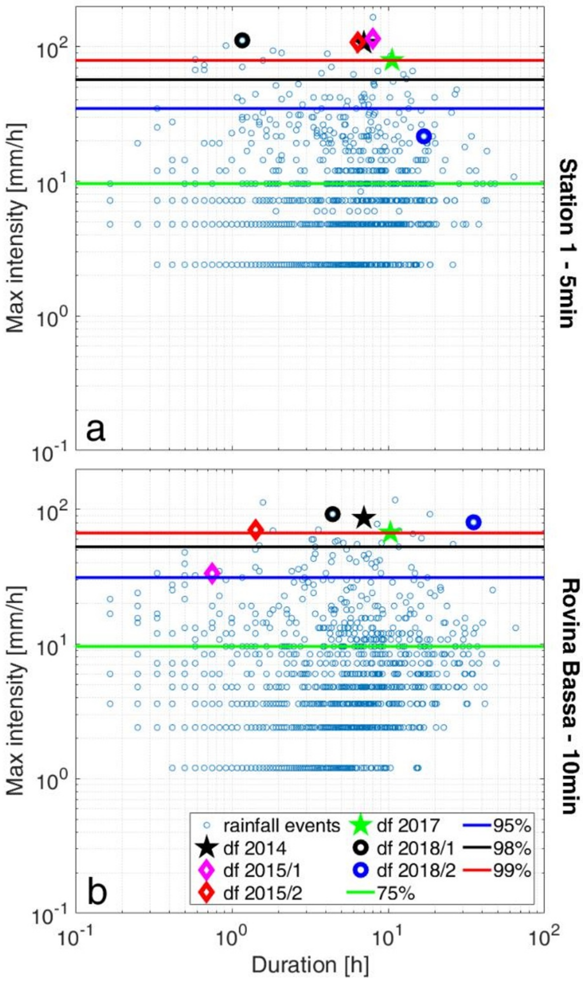

Fig. 3. Example of event characterization on a population of max intensity per 5-min (a) and 10-min (b) interval per each automatically identified rainfall event, data are related to station 1 (a) and Rovina Bassa (b) gauges. Looking at the 2018 event, it quickly emerges as a very severe contribution from 10 minutes up to all the considered durations especially in the lower Rovina Bassa station notwithstanding the frontal long lasting precipitation type.

While we could not use debris-flow occurrence time information (available only for a handful of events) we could however investigate rainfall properties in the range 5-min/48-h (5, 10, 15, 30, 60 min and 1, 3, 6, 12, 24, 48 hours) for each event, showcasing the statistical properties of those events that have actually triggered a debris flow. This permits the characterization of rainfall properties independently from event duration or total accumulation metrics that may suffer from the choice of different hiatuses or minimum rainfall depth for event definition.

For all the analyzed events, debris-flow related rainfall popped up as an extreme value at least for one rain gauge location considering the percentile distribution of the analyzed intervals in respect to the average population severity, and this was true from the 5-min interval up to the 1-h and 3-h durations for typical summer events (Fig. 3). This satisfactory detection capability can be ascribed to the optimal spatial arrangement of the rain gauges. The upper twin rain gauges (station 1), close to the initiation areas, record rainfall intensities higher than the other rain gauges during severe summer convective events (Fig. 3a), whereas the lower rain gauge (Rovina Bassa) better detects the most severe conditions related to frontal precipitation events (Fig. 3b). The middle rain gauge (station 2) exhibits an intermediate behavior with good detection capabilities of both types of events. Such a combination of “event-sensitivity” has thus the intrinsic potential of detecting almost the whole spectrum of conditions that can lead to debris-flow initiation in Cancia.

More in general, gauge location is always one of the key points for reliable thresholds development since having at least one rain gauge close to the catchment centroid is crucial for a proper spatial rainfall calibration even when using distributed measures such as radar-derived rainfall maps [11].

In the case of Cancia, after having verified that all the debris-flow events featured at least one rainfall intensity interval very close or above the 99 percentile of the dataset, the 95, 98 and 99 percentiles of each gauge location and each considered time interval were retrieved from the analyzed populations and integrated within the operational EWS associated with an increasing level of pre-alert severity. It is worth mentioning here that also some previous studies in the dolomitic area [3] identified rainfall intensity duration curves that fall roughly in the 98-99 percentile range thus demonstrating the mutual robustness of the proposed approaches.

Regarding the seismic dataset, the travel time of the major debris-flow events was calculated, and a first-order volume estimation was proposed based on the integrated seismic energy detected by a single geophone [12]. An amplitude-based event threshold was identified but, due to hardware limitations though, a dynamic threshold based on moving windows computation was not workable thus removing a degree of reliability to the proposed thresholds. Anyway, the integration within the EWS of seismic data thresholds has the advantage of providing an alert in advance and detecting also minor events or short travelling ones thus increasing the overall robustness of the system.

4 Approach implementation and perspectives

The proposed thresholds together with related operational measures (SMS with increasing alert level) were tested during the 2020 season leading to a positive evaluation of their performance. Rainfall severity was classified by percentile rank with different levels of pre-event warning related to the 95, 98 and 99 percentiles.

Operational measures took also into consideration a pre-event condition and a post-event one (trip wires interrupted) allowing the seismic and level values to directly issue a warning in the post-event scenario. In particular, during the 2020 season only a few minor events occurred in the catchment (July, 1st, August 20th and 29th). Such events were characterized during post-event field surveys and monitoring cameras image differencing since they did not have a magnitude capable of stressing the whole system and delivering significant amounts of debris to the channel outlet.

Notwithstanding this, the developed thresholds revealed their effectiveness also in the detection of such minor events proving their reliability without raising, for the 2020 testing season, any false alarm. As a future perspective, the continuously increasing rainfall events population could be further analyzed so as to verify which statistical property (or other paradigms such as peak-over-threshold approaches) might better represent debris-flow triggering rainfall and to attain even more refined initiation threshold.

Finally, the collaboration among authorities, decision-makers and researchers on such issues can be regarded as the way forward, helping also in the transition from a catchment-scale EWS perspective towards a more comprehensive valley-scale risk management. This is true especially in light of the ongoing investments in the area for the first European smart road (Cortina 2021 and current developments, details at: https://www.anaspercortina2021.it/smart-road-cortina-2021) that will pave the way for a new generation of resilient infrastructures capable of sensing the environment and broadcasting warnings at the onset of an hazardous event.

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