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A model-based early warning system for runoff-generated debris-flow occurrence: preliminary results

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Abstract. Early warning systems for debris flows are low cost measures for mitigating this kind of hazard. The early warning systems provide a timely alert for upcoming events in order to take protective measures, such as closing railways-roads, evacuating people from the threatened areas, and put rescue forces into readiness. These systems usually are sensor-based, and the alert time is the interval between the timing of the first detachment of debris flow by a sensor and its arrival into the threatened area. At the purpose of increasing the alert time, we propose an early warning system based on a model-cascade: nowcasting, hydrological- and triggering models. Nowcasting anticipates rainfall pattern that is transformed into runoff by the hydrological model. The triggering model estimates the volume of sediments that the runoff can entrain, and compares it with a critical threshold. If this is exceeded the alert is launched. The proposed early warning system is tested against the available data of the Rovina di Cancia (Northeast Italy) site.

1 Introduction

Early Warning Systems (EWS) are basically integrated systems of forecasting, hazard monitoring and communication, enabling organisations to take timely actions to reduce disaster risks as minimizing loss of life and damages in case of hazardous events. In essence, the EWS provides an alert on a future or on ongoing event [1]. The increasing occurrence of extreme precipitation causing debris flows, induced by climate change effects, points to a wider and wider use of EWSs as mitigation measure for the risk management [2]. This system has no marked negative effects on landscape or ecology, and it is more flexible than structural countermeasures characterized by high costs, that for this reason can be implemented only with limitations [3,4]. An EWS for debris-flow occurrence is usually sensor-based, and it is composed by a monitoring system linked to a communication system. When the monitoring system detects an ongoing event, the communication system provides the alert to the managing authority and/or directly to the population by means of sirens and traffic lights on the vulnerable roads. The monitoring system usually consists of one or two types of sensors: i) sensors recording the rainfall that triggers the debris flow, such as rain gauge and weather radars, and ii) sensors detecting the transit of the debris flow: trip wires, geophone, and flow level sensors (radar, laser, acoustic, pressure transducers). The first type of sensors can spread the alarm about 10 to minutes on average before the debris-flow trigger (the time for runoff generation depends on terrain characteristics and morphology as well as by moisture conditions and moisture) by comparing the measured precipitation with an intensity thresholds. Conversely, sensors of the latter type can provide the alert between 1 to 20 minutes, on average, before the debris flow impacts the threatened area. As the alert time (i.e. the interval between the debris-flow detection and its reaching areas the threatened area) is crucial to take adequate civil protection measures, it should be extended as much as possible. The sensor-based EWS has the limit of the alert time that is imposed by lag time between rainfall occurrence or debris-flow transit detection, and debris-flow arrival into the area to protect. In order to increase the alert time, [5] successfully used a 1h-nowcasting system based on portable weather-radar for the identification and tracking of storm cells. When the rainfall intensity of the identified cells exceededs the threshold value for debris-flow occurrence, they were able to launch the alert at least one hour in advance. The solution adopted by [5] can be used if the identification and tracking of cell storms is possible. In order to increase the alert time in each situation, the Interreg Italy-Austria program funded the project INADEF (Innovative eArly warning system for Debris Flows, 2019-2022) to develop a EWS based on a cascade of models that provides the rainfall pattern, the generated runoff volume and the corresponding sediments volume of debris flow.

2 The proposed model-based EWS

The proposed EWS for debris-flow occurrence is composed by a cascade of models integrated into a web application (Figure 1). The cascade of models simulate the rainfall pattern six hours in advance, nowcasting the runoff generation and the triggering of debris flow with an estimate of the potential sediment volumes. The nowcasting is provided by INCA (Figure 1 *i.*) [6], a multi-parameter analysis and nowcasting system for meteorological parameters, developed by ZAMG. Based on the spatial and temporal pattern of precipitation (Figure 1 *ii.*) the runoff is calculated with the conceptual precipitation-runoff model ZEMOKOST (Figure 1 *iii.*) [7]. According to the channel network, sub-catchments are defined and information on roughness, runoff coefficient, and terrain specifications (area, inclination, etc.) are surveyed.
For each sub-catchment, the calculated hydrograph is forwarded to the sub-catchment area below until the last node in the spatial description is reached (Figure 1 *iv.*). The model provides the input for the debris-flow triggering model (Figure 1 *v.*), discharges in m^3/s every minute, and for each sub-catchment.

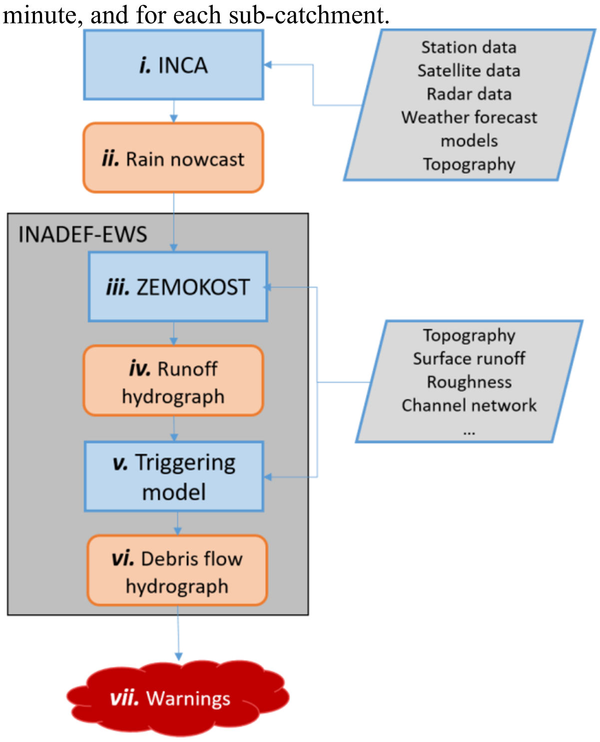

Fig. 1. The INADEF architecture.

The triggering model estimates by means of the mass conservation equation the potential entrainable sediments volume associated to the runoff volume contributing to debris flow (Figure 1 *vi.*), that is the runoff volume corresponding to a discharge larger than a critical threshold for debris-flow initiation [8]. The parameter controlling the volume of entrainable sediments is the sediment concentration *c*. This value depends both on rheology and site morphology (i.e., the channel length from the initiation area to the threatened area). The EWS operates at two levels: it forecasts the debris-flow occurrence and estimates the event magnitude. The first level corresponds to the comparison of runoff discharge with the critical threshold, while the second level derives from the comparison of the computed volume of sediments with a threshold. This threshold is the value of the sediment volumes of the debris flow that stops just upstream of the threatened area and it is site-dependent. When each threshold is exceeded, the corresponding alert is launched (Figure 1 *vii.*).
Since the model cascade needs to be executed for each nowcasting timestep, an online server was selected as the best solution to make the EWS operational. Therefore, a Web-Gis Application (WGA), was designed and implemented, with a back end in charge of orchestrating the model's cascade, and a front end to disseminate the simulation results (Figures 2 and 3).
The system operates as follows (Figure 1): *i*) INCA uploads updated 6-hours rainfall nowcasting every 15 minutes on the INADEF server. *ii*) When a new nowcasting is uploaded, the WGA extracts the information it needs from the nowcasting grids and *iii*) feeds it (along with other information about the study sites) to the hydrological model ZEMOKOST). *iv*) The results of the hydrological model are used as inputs for the triggering model (*v*), and *vi*) the results of the triggering models are analysed. When a debris flow is forecasted for a site *vii*) the web app displays a warning, on a map and notifies selected recipients via e-mail.

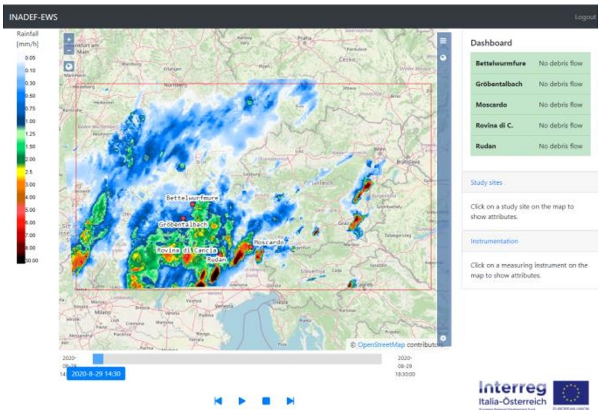

Fig. 2. The web app front end showing the INCA rainfall nowcasting maps and the INADEF study sites

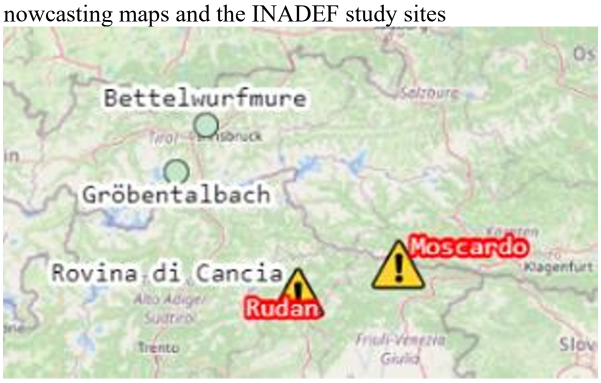

Fig. 3. A close-up of the web app front end: on the map the study sites where a debris flow is forecasted, are highlighted.

3 The site of Rovina di Cancia

The EWS was tested on five test sites, three in Northeast Italy (Moscardo, Rovina di Cancia and Rudan), and two in Austria/ Tyrol (Bettelwurfmure and Gröbentalbach, Figure 3). In the present work, we only show the test bed site of Rovina di Cancia because it is the site with the larger number of events, and therefore, it can provide more reliable results.

The first known debris-flow event in Rovina di Cancia [9] is dated 1868, when a catastrophic debris-flow of about 100,000 m^3 caused 21 victims. Debris-flow occurrence increased in the last ten years. The Rovina di Cancia channel originates on the scree at the feet of Salvella Fork (2500 m a.sl.). The upper part of the channel is covered by giant boulders and water surges delivered by rocky cliffs cannot entrain large quantities of sediments. This occurs around and downstream the giant rock at a quote of 1666 m a.s.l., where some tens of thousands of sediments can be entrained. A flat area at a quote of 1330 m a.s.l. stops debris flows transporting a sediments volume up to 10,000 m^3 and reduces the solid content of events transporting larger volumes. Downstream of the flat area there is an open check dam that dampens the erosion of the upstream reach, and, just downstream of it there is the confluence of the Bus de Diau Creek that drains the basin identified by the yellow border in Figure 4 (the basin contributing to the initiation area is identified by the red borders). The channel ends at two retention basins that protect the downstream inhabited area. Most of the sediment entrainment occurs between the initiation area and the flat area. Downstream of the open check dam, debris flows alternate phenomena of entrainment and deposition. A monitoring station (n.1 of Figure 4) and rain gauges were installed in 2014, while another two monitoring stations were installed in 2019. The monitoring stations were upgraded in 2020 with infrared cameras and flow level sensors (radar and laser meter) during INADEF project. During the project period three debris flows occurred: on 1 July, 11 and 29 August 2020. The corresponding mobilized sediments volumes were estimated by differencing the pre and post-event Digital Elevation Models (DEMs) obtained from Unmanned Aerial Vehicle (UAV) photogrammetric surveys. At this site a sensor-based EWS [10,11], that is not displayed in Figure 4, is operating as well.

4 Testing of the EWS

The EWS was tested for the period 2009-2021, were ten debris flows occurred. Before running the nowcasting, the single couple hydrological-triggering model is tested using the rainfall data of the rain gauges, the estimated volumes of entrained sediments, and the timings of debris-flow occurrence. The value of the sediment concentration for computing the potential entrainable sediment volume is 0.5. This is the value of the main parameter of the triggering model for computing the debris-flow hydrograph. Such a value is the maximum one obtained by the comparison between the estimated sediment volume and that computed through the relationship that provides the potential entrainable volume. Using c = 0.5, the model-cascade hydrological-triggering model is runned for all the ten occurred events of debris flows.

The overall comparison provides satisfactory results. At the first level, all events are identified. In addition, the difference between the estimated and predicted occurrence times ranges in the interval [-8 - +8] minutes with a mean value of 4.5 minutes. The comparison between the volumes of sediments predicted by the model cascade and those estimated is shown in Figure 5.

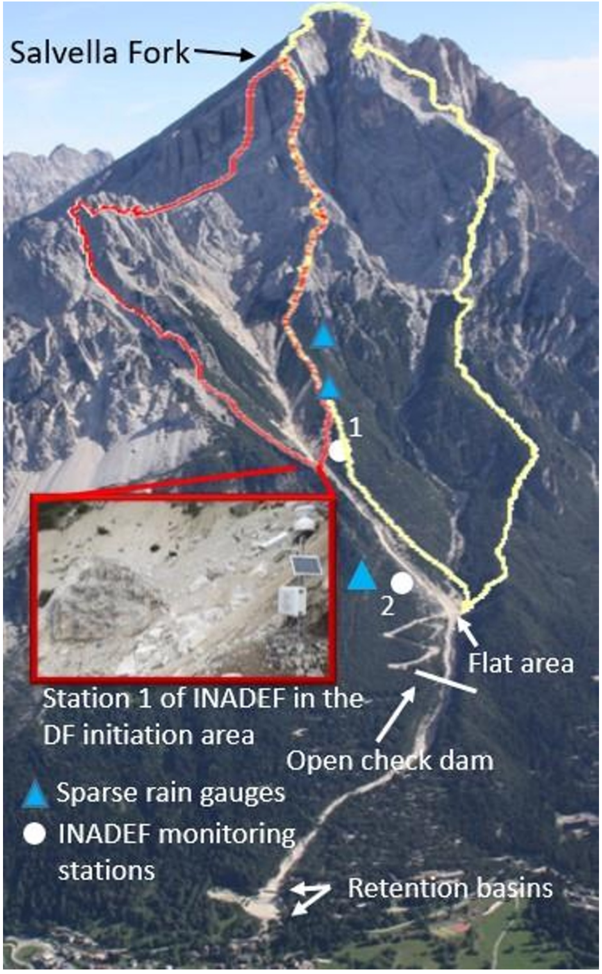

Fig. 4. The site of Rovina di Cancia with the rain gauges (triangles, dark of ARPAV and white of INADEF) and the numbered monitoring stations (circles) used for testing the WGA. The red and yellow lines identified the basins drained by the initiation area and the mouth of Bus de Diau Creek, respectively.

At the second level, the volume of an unique occurred event is underestimated and such an event results to be below the threshold almost certainly because the missing of recorded rainfall pattern on the basin contributing to the triggering area; two values of the predicted volumes of sediments are overestimated and over the threshold. This means that there is one missed alarm and two false alarms on ten events in twelve years.

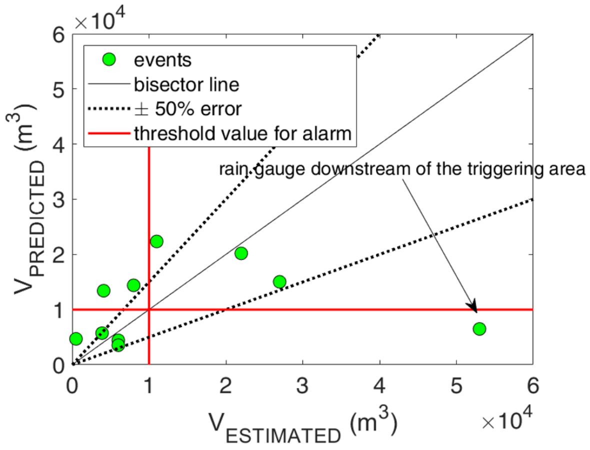

Fig. 5. Comparison between the estimated and predicted sediment volumes for the occurred events using the observed rainfall pattern.

The EWS is then tested using the whole model cascade, using therefore, the rainfall pattern provided by nowcasting for the period 2009-2021.

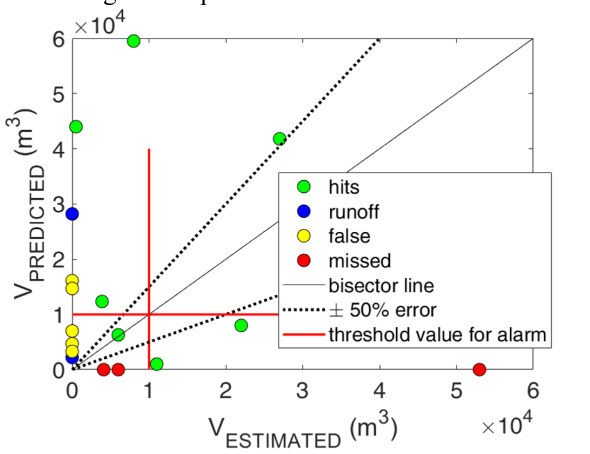

Fig. 6. Comparison between the estimated and predicted sediments volumes in the period 2009-2021.

Figure 6 shows the comparison between the sediment-volumes of debris flows predicted by EWS with those of the estimated volumes of occurred debris flows for twelve years. The green circles correspond to the sediments volumes both predicted and estimated. This case represents the relative majority of the events. It is followed by the case of false events (yellow circles), missed events (red circles), and runoff events (blue circles). About the first level, i.e. the debris-flow forecasting, the performance of the EWS is quasi satisfactory because in a period of 12 years there are five false alarms (runoff events are assimilated to those of debris flows) and three missed events: about one each two and four years respectively. The ROC analysis, in fact, provides the following values for true positive, true negative, false positive, and false negative rates: 0.77, 0.88, 0.12, and 0.3 respectively (for the ROC analysis the runoff events are treated as false events). About the second level, i.e the prediction of the sediments volume, the performance of the EWS is not satisfactory because it captures only a high magnitude and a low magnitude event. However, most of the false and missed events are below the threshold for alarm.

5 Conclusions

A model-based EWS for debris flow is proposed and tested in a monitored basin in a period of twelve years, in which ten events of debris flows were observed. The model cascade using the observed rainfall is tested satisfactorily. Conversely, the model cascade using the nowcasting has a lower performance in terms of predicted sediments volume but a satisfactorily one in terms of predicted events. These are initial results. A substantial improvement of the event prediction quality in the single catchments can be achieved by the calibration of the model by (extensive optical) event monitoring. Moreover, the permanent ongoing development of the precipitation-forecast as important input parameter should rise the hitrate as well.

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