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Simulations of the occurrence of runoff-generated debris flows by means of hydrological models in headwater rocky basins

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Abstract. The simulation of the occurrence of the runoff-generated debris flows can be approached by means of hydrological models. In this work, we show that a rainfall-runoff model designed for the simulation of runoff in headwater rocky basins can capture both the transit timing of the first debris-flow surge and its hydrograph. We successfully compared the stage hydrograph of debris flows with that of the simulated runoff in two headwater rocky basins of Dolomites.

1 Introduction

In the Dolomites area (Eastern Italian Alps), sub-vertical rocky cliffs generate notable discharges during summer thunderstorms, often triggering debris flows on the screes at their base. Cliffs are incised by several chutes where runoff usually concentrates. At their base, debris flow channels start, originated by the erosive activity of both runoff and mass transport phenomena. The forecasting of such events has great significance for reducing damages and victims in the exposed areas. Predictions could be performed by the combined use of hydrological models and debris-flow triggering thresholds, distinctive for each watershed. In fact, according to [1], rainfall-runoff models can emulate the timing of debris-flow transit. Herein, we show that the model of [2] can approach the hydrograph of the first debris-flow surge, downstream of the initiation area of different scale basins in a dolomitic environment.

2 Material and methods

2.1 The rainfall-runoff model

The rainfall-runoff model of [2] is a distributed hydrological model that computes the excess rainfall and routes it to the outlet for each cell of the digital elevation model of the considered catchment. The flow path is subdivided into slope and channel paths. Along slope paths, it is assumed a constant velocity, U, depending on the terrain land use, whereas along channel paths the routing is modelled using the matched diffusivity kinematic model of [3]. Excess rainfall is computed through either a simplified Horton's law when rainfall intensity exceeds infiltration rate f_C or by using the SCS - CN method. The model parameters, which refer to the generation and the propagation of runoff in the considered basin, are the curve number *CN*, the infiltration rate f_C, the along-slope velocity *U* and the Gauckler-Strickler coefficient K_S.

The model has been calibrated against runoff discharges estimated at the outlet of a channel incised on a rocky cliff, not too far from the investigated basins (Dimai catchment in the inset of Figure 1). All the values of the parameters are shown in Table 1. The initial abstraction *Ia* of the SCS-CN method is assumed equal to 0.1*S* (S is the potential maximum retention and it depends on CN). The value of f_C, in the case of rocky terrain, is provided by the following equation [4]:

$$f_C = 3.12 - 0.15\,P \tag{1}$$

where *P* denotes the cumulated rainfall recorded in the 2 days preceding the event (in mm). This relation is effective only for AMC I events.

Table 1. Calibrated parameters for the hydrological model.

Parameter	Rocky surface	Mountain pine slopes	Scree slopes
CN	90.4	61	65-70
U (m/s)	0.7	0.05	0.1
K_S ($m^{1/3}$/s)	9	9	9
f_C (cm/hr)	Eq. (1)	5.5	10.8

2.2 The debris-flow sites with the monitoring activities

The debris-flow monitored sites are those of Rovina di Cancia (hereinafter Cancia) [5] and Rio Gere [4,6]. In these sites, two monitoring stations are operating since 2014 and 2021 respectively. The two stations are

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positioned in the upper part of the catchments, just downstream of the initiation area of the debris flows. Both stations are equipped with a rain gauge, flow level sensors and cameras. The sampling interval of all sensors but the cameras is five minutes. If the rainfall depth estimated at intervals of 2.5 minutes overpasses the cumulative threshold value of 0.6 mm, the sampling interval decreases to five seconds for the following two hours and cameras start a continuous image acquisition. The monitored headwater basins represent the typical sizes of dolomitic watersheds, ranging in the interval 0.5 – 1.0 km^2 (their morphological features are resumed in Table 2). The presence of other standalone rain gauges completes the instrumentations of the areas, allowing better observation of the spatial distribution of rainfall in the watersheds. Figure 1 shows the two basins with the position of rain gauges and monitoring stations.

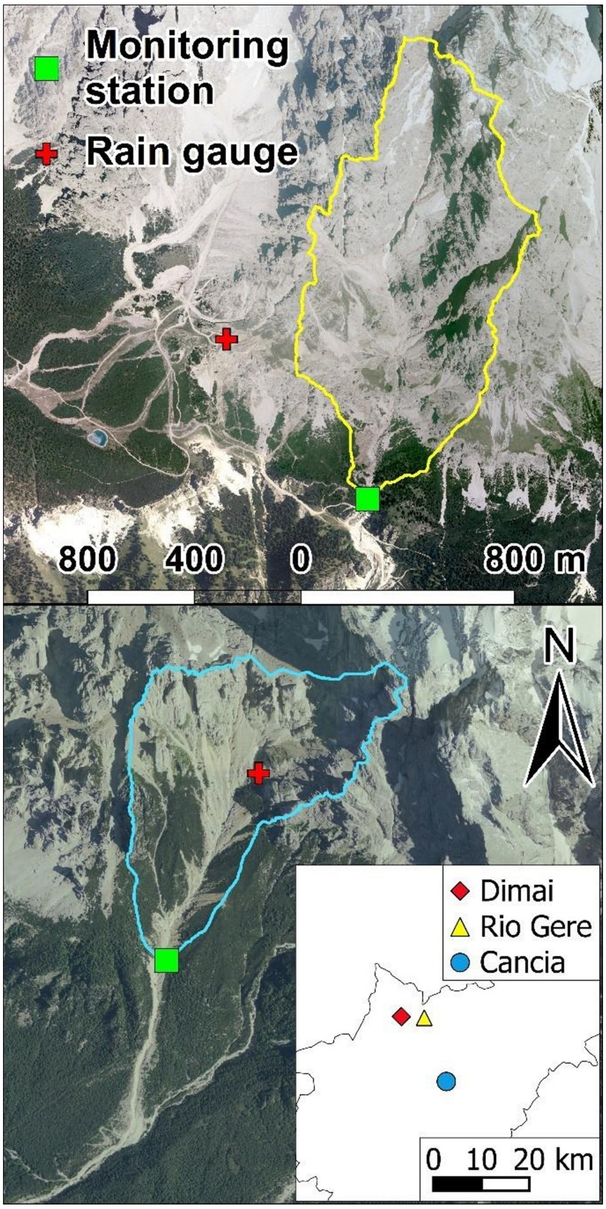

Fig. 1. Rio Gere (top) and Rovina di Cancia (down) basins closed at the triggering areas of debris flows with the position of monitoring stations and standalone rain gauges. In the insert, the location of the basins in the province of Belluno (Italy) with reference to the Dimai basin where the hydrological model was calibrated.

Table 2. Morphological features of the monitored catchments.

	Cancia	**Rio Gere**
Area (km^2)	0.65	0.93
Min elevation (m a.s.l.)	1662	1932
Mean elevation (m a.s.l.)	2213	2500
Max elevation (m a.s.l.)	3067	3220
Mean slope (°)	54.2	50.6
Max slope (°)	87.8	89.3
Channel mean slope (°)	36.5	34.3
Land use		
Bare rock	50%	70%
Scree and active erosion	28%	23%
Moors and heathland	22%	7%

2.3 The recorded debris flows

Since their setting up, various debris-flow events occurred in the monitored catchments. In the Cancia basin, eight debris flows occurred since 2014 but only in three cases, a stage hydrograph has been recorded: on July 23rd, 2015; on August 1st, 2018; on July 1st, 2020. In the Rio Gere catchment, one hyper-concentrated event occurred on July 8th, 2021. In this work, we focused our attention on the last three events because the debris flow that occurred in Cancia on July 23rd, 2015, has been analysed in detail in [5]. In Table 3, we indicate the characteristics of the precipitation, which triggered the reported debris-flow events, as recorded by the monitoring stations. Rainfalls have been identified as suggested by [7], i.e., storms with gaps between consecutive rain gauge tips lower than 10 min.

Table 3. Characteristics of the precipitations that triggered the phenomena occurred on August 1st, 2018; July 1st, 2020; July 8th, 2021, as recorded by the monitoring stations. D and P indicate the duration and depth of rainfall, I the mean intensity, $I_{MAX,t}$ the max intensity recorded in a *t*-minutes interval, D_{TRIG} and P_{TRIG} the duration and depth of rainfall up to the triggering of the hydrogeomorphic processes.

	August 1st, 2018	**July 1st, 2020**	**July 8th, 2021**
D (h)	1.0833	0.8333	2.0833
P (mm)	37.8	18.2	29.6
I (mm h^{-1})	34.89	21.84	14.21
$I_{MAX,5}$ (mm h^{-1})	129.6	96.0	81.6
$I_{MAX,15}$ (mm h^{-1})	99.2	65.6	46.4
D_{TRIG} (h)	0.5000	0.5000	0.5833
P_{TRIG} (mm)	30.2	17.2	13.6

3 Results

In Figure 2, we plot the hydrographs simulated by the rainfall-runoff model of [2] against the stage hydrographs recorded by the two monitoring stations. The stage hydrographs were measured differently, depending on the operative sensors at the time of the events: in Cancia, stages have been derived by a pressure transducer for the event that occurred on August 1st, 2018 (Figure 2a), whereas by a video reconstruction for the debris flow on July 1st, 2020 (Figure 2b). For the hyper-concentrated flow that occurred in Rio Gere on July 8th, 2021 stages have been recorded by a laser-level sensor. Each sensor has pros and cons: the pressure transducer is quite reliable in terms of the transit timing of an event but its recording duration is generally short because it risks being torn off by the phenomenon. The video reconstruction of a debris-flow event permits a correct detection of the transit timing of an event but it is the least reliable in terms of stage values due to the uncertainties in determining the heights of the phenomenon; moreover, footages recorded at night are hardly usable. Lastly, the laser sensor detects the timing with precision and the stages with continuity but it could give wrong height values when the surface of flow is highly irregular.

The comparison between simulated discharges and recorded stage hydrographs is made in terms of time and shape. The lag time between the peaks of simulated runoff and the transit of the first surge of observed debris flows (estimated as the time that maximizes the cross-correlation between the two series) ranges in the interval [-2.5, 1.5] minutes. These outcomes are consistent with the inception mechanisms of debris flows that are strictly related to the destabilizing action exerted by runoff on in-channel sediment layers. Hence, a small time lag between the hydrograph peak simulation and the triggering instant of debris flow implies a rather robust performance of the rainfall-runoff model. Moreover, the simulated discharges reproduce quite entirely the stage hydrographs except for the last part of the recordings. In these segments, modelled runoff is lower than the considered critical threshold. Hence, runoff cannot entrain sediments and, consequently, should not be considered in the evaluation of liquid volume contributing to the debris-flow solid-liquid wave.

These findings completely agree with those of [1], who compared the peak times of modelled discharges with those of corresponding stage hydrographs of occurred debris flows, concluding that hydrological models can emulate the initiation time of runoff-generated debris flows. This similar behaviour took place although the difference in the implemented excess rainfall generating process, due to the distinct features of the analysed catchments. [1] evaluated excess rainfall by means of the Green-Ampt approach, i.e. a saturation-excess runoff production mechanism, whereas we used an infiltration-excess method, as the Horton equation.

The capability of the developed model to catch the runoff peak time and the evolution of the debris-flow first-surge stage with good accuracy suggests a potential use in early warning systems for evaluating the debris-flow occurrence. An application could be the estimation of the solid-liquid hydrograph, after assuming a characteristics value for the solid volumetric concentration of the phenomenon: runoff contributing to the debris-flow initiation and the corresponding solid-liquid hydrograph could be determined and propagated by means of debris-flow routing models. A reliable estimate of entrainable sediment volume and, consequently, of the potentially inundated areas is fundamental to hazard assessment and risk evaluation, the design of appropriate structural countermeasures, and the development of efficient emergency management regulation.

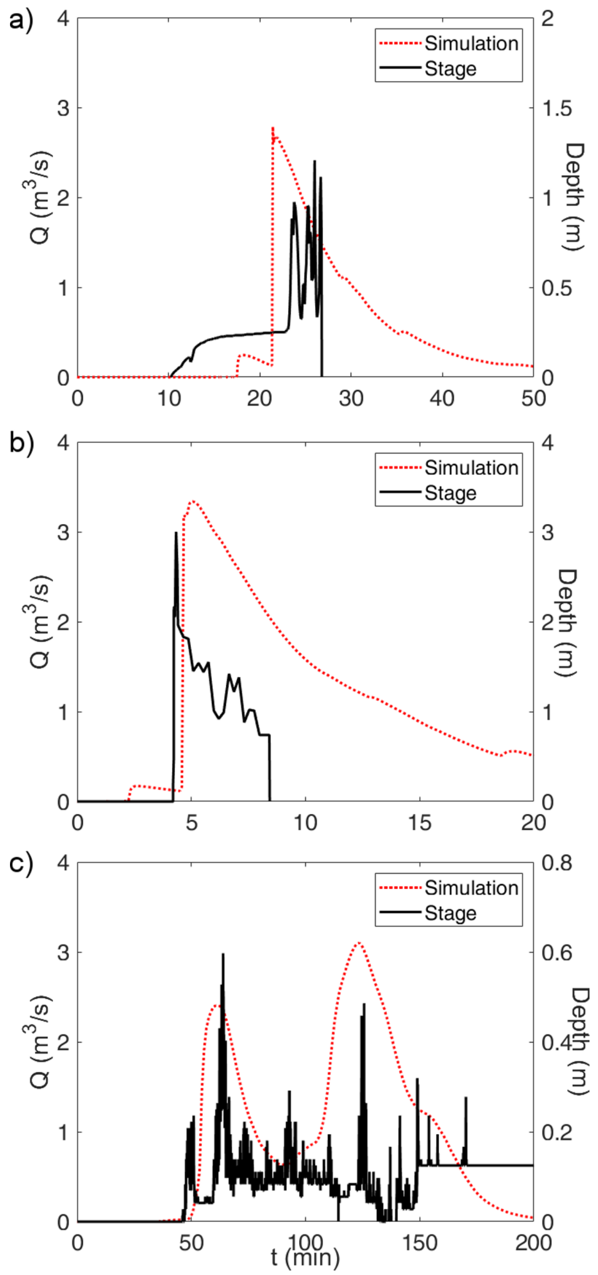

Fig. 2. Events recorded by the monitoring stations of Rovina di Cancia on (a) August 1st, 2018 and (b) July 1st, 2020 and of Rio Gere on (c) July 8th, 2021 and relative hydrological simulations. The stage hydrographs have been derived from (a) pressure transducer, (b) video cameras, and (c) laser level sensor.

4 Conclusions

The impervious morphology of dolomitic headwater catchments makes monitoring activities challenging. The knowledge of discharge behaviour is fundamental both for improving the comprehension of debris flow triggering and for modelling the initiation dynamics on the scree slopes at the base of rocky cliffs. We documented the hydrological response of two catchments to three convective rainfall events. Observed debris-flow hydrographs exhibit an impulsive character. A hydrological model has been tested to reproduce this behaviour. Simulated discharges have been compared to the stage hydrographs of observed debris flows in the Cancia and Rio Gere catchments. The robustness of the model has been tested by comparing the simulated runoff peak times and the timing of debris flows. Differences in timing result in a few minutes. Moreover, runoff replicates quite entirely the recorded stages, except when discharges decrease below the triggering threshold of debris flows. These results ensure reasonably good predictability of the model, permitting its potential use in the evaluation of debris-flow solid-liquid waves in early warning systems.

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