1 Debris flow triggering characterization through a
2 comparative analysis among different mountain
3 catchments

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8 **Abstract**

9 The research focuses on the assessment of the conditions for debris flow triggering
10 in three very active mountain catchments. The study areas are the following:
11 Rudan torrent (Vodo di Cadore, Mount Antelao in the Dolomites, Italy), Chiesa
12 torrent (Pieve di Livinallongo, Mount Col di Lana, in the Dolomites, Italy) and
13 Rebaixader torrent (border between the regions of Catalonia and Aragon, Axial
14 Pyrenees area, Spain). Thanks to the differences among these basins and related
15 source areas where debris flows originate, the knowledge on the link between
16 geomorphic conditions and driving mechanisms for debris flow activation is outlined.
17 The study of debris flow initiation is carried out through a hydrological
18 approach and a slope stability analysis. The hydrological analysis is supported
19 by the calibration of intensity-duration curves of triggering rainfalls coupled with
20 a distributed rainfall-runoff model. The analysis is corroborated using literature
21 equations to compute critical discharges for sediment motion at the different levels
22 of terrain deformation. Main results highlight: i) a quite narrow range of triggering
23 water discharges (0.03-0.16 m³/s) and shear stresses (267-413 N/m²), promoting
24 a new insight on the specific hazard mitigation, ii) the quantification of a

second stage of bed-breakage capable in some circumstances to amplify the debris flow magnitude; iii) a minimum critical rainfall duration needed to effectively entrain the phenomenon (12-22 minutes) and that might help to define more precise alert conditions. Finally, the geomorphologic differences among basins revealed two main typologies in terms of driving triggering mode: flow rate dominant in the Rudan-type basins and mixed (flow rate plus slope stability conditioned) in the Chiesa-Rebaixader type basins.

Keywords: Debris flow initiation, Runoff, Headwater basin, Hydrological modelling

1. Introduction

Debris flows are mixed masses formed by rocks, mud, water and air that move with relatively rapid velocities inside steep channels in mountainous catchments [1]. This type of mass movement has become one of the most dangerous threats for alpine valleys [2, 3]. Thanks to the general economic development of the last century [4], there has been a relevant expansion of human settlements in unstable mountainous areas. Therefore, studies on debris flows have become crucially important because of the economic and social losses that these phenomena can cause. In recent years, many studies have concentrated on the modelling of torrential flows [5, 6, 7, 8, 9, 10, 11], giving particular importance to the triggering of debris flows events. The triggering mechanism is a complex phenomenon that depends on different variables. Many studies [12, 13] have reported that the three most important variables for the triggering of a debris flow are slope gradient, sediment availability [14, 15] and water input. Therefore, for a basin never limited by the first two variables, water input plays the most important role. There can

49 be different types of water input, like for example outburst floods, or snow melt
50 or rainfall events. In the present study we focused in particular on the last one
51 because if the rainfall is strong enough, the water inside the channels can reach a
52 critical discharge in which the mobilization of sediments starts [16, 17, 18, 19].

53 Considering the hydrological response of the catchment to precipitation, two
54 main types of debris flow triggering events have been described: (1) channel-bed
55 failure and (2) shallow slope failure.

56 1. The first type happens when a debris flow originates from an initial gully
57 erosion that rapidly evolve in a massive erosion of both the channel bed
58 and channel banks caused by a superficial runoff fast removing shallow
59 layers mostly. In addition, [20] described a sub-type of channel-bed fail-
60 ure, which happens when the debris flow material is not derived from an
61 erosional mechanism but is derived from the mobilization of previously ac-
62 cumulated loose debris inside the channel (dam-break mechanism). Such
63 material moves because it is liquified and/or is overflowed by erosive water
64 discharge.

65 2. The second type happens when a shallow landslide caused by the rapid in-
66 filtration of water in the superficial soil layers develops in a debris flow. In
67 fact, the subsurface water can partially saturate soil, taking the material near
68 the critical stability conditions [21, 22, 23, 24] and destabilizing the near-
69 surface layers composed of less compact sediments. These types of terrain
70 mobilization can evolve into debris flows if slope failure happens in a zone
71 of the basin connected [25] to the channel network [2].

72 Therefore, to investigate in particular the first type of initiation mechanism, it
73 can be useful to find the rainfall intensity and duration needed to reach the critical

74 discharge inside the channel. For this purpose, the maximum rainfall intensity-
75 duration equations related to the triggering of torrential flows are particularly rel-
76 evant. Precipitations with an intensity greater than the one described by these
77 curves can potentially initiate sediment mobilization. Many studies carried out in
78 the last few decades have proposed several rainfall thresholds based on different
79 study areas [26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36]. Moreover, many stud-
80 ies have concentrated on the analysis of the critical water discharge needed for
81 the in-channel mobilization of sediments [37, 38, 19]. Therefore, coupling these
82 two approaches (intensity-duration equations and critical water discharge), we can
83 achieve the following goals: (1) make significant improvements on understanding
84 the conditions needed to trigger debris flows in real case study areas; (2) under-
85 stand the link between the trigger type and respective most effective forcing. The
86 advantage of this type of study is that we can estimate more precisely the critical
87 rainfalls and related discharges in order to take correct decisions on the manage-
88 ment of debris flow hazard, whereas the limitation is that the results depend on
89 the quality of the topographic data and on the intensity-duration equation chosen.

90 In the present work, we selected three different catchments: the Rudan torrent
91 (Mount Antelao) and the Chiesa torrent (Col di Lana) in the Eastern Italian Alps
92 and the Rebaixader torrent in the Spanish Axial Pyrenees. The catchments show
93 different morphological and geological settings, and so their response to water
94 input varies because the catchment morphology has a great influence on runoff
95 initiation [39]. Therefore, it is relevant to study such different catchments because
96 the comparison of their behavior is likely more instructive than a regional case
97 study where the basin sample would be more homogeneous.

98 The main aim of this study is to verify how the triggering conditions may vary

99 among basins with different geological and morphological conditions. In partic-
100 ular, we analyzed the following questions: (1) what is the minimum rainfall du-
101 ration over a given threshold intensity that can generate a critical discharge inside
102 the channel network? (2) What is the range of critical discharges that can trigger
103 a channel-bed failure debris flow in the analyzed areas? (3) How relevant is the
104 shallow-slope failure mechanism in the destabilization of the studied headwater
105 basins and triggering areas?

106 **2. Study areas**

107 *2.1. The Rudan catchment*

108 The Rudan torrent is one of the main channels that flows down from the South
109 side of Mount Antelao (3264 m a.s.l.) (Fig. 1). This torrent is located in the
110 municipality of Vodo di Cadore (BL, North-Eastern Italy) and has an area of 2.71
111 km². The channel starts just below the peak of the mountain, inside a great source
112 area named “Vallon dell’ Antelao”, and flows down until confluence with the Boite
113 torrent. The catchment has a wide elevation range from 3229 m a.s.l to 788 m
114 a.s.l [40]. The mean annual precipitation of the basin is 1130 mm and the mean
115 number of rainy days per year is 110 (data collected between 1985 and 2018
116 by the meteorological station of ARPAV – Regional Agency for Environmental
117 Prevention and Protection of Veneto – located in Borca di Cadore, BL - WGS84
118 coordinates: 12.2° E, 46.4° N).

119 In the past, the catchment has experienced very strong torrential events. His-
120 torical documentation describes catastrophic debris flows that completely buried
121 and destroyed ancient villages [41]. In addition, in the last decades, the catchment
122 has suffered debris flows that damaged the municipality and the National Road 51

123 "di Alemagna". For this reason, in 2011, a filter check-dam with a storage basin
124 was built just above the street (Fig. 1). Mainly dolomitic rocks characterize the
125 geology of the basin, especially in the upper part.

126 In the hydrological modelling area (Fig. 6), we analyzed the soil matrix, con-
127 sidering as "matrix" the finer part of the soil, excluding pebbles and boulders. In
128 particular, we used the following classification: pebbles if the diameter is greater
129 than 60 mm; gravel when the diameter goes from 2 to 60 mm; sand when the di-
130 ameter goes from 0.075 to 2 mm; silt when the diameter goes from 0.002 to 0.075
131 mm and clay when the diameter is finer than 0.002 mm. The soil matrix in the
132 source area of the Rudan catchment (triggering area shown in Fig. 1 and Fig. 6) is
133 mainly composed of gravel and sand, whereas only a small percentage of the ma-
134 trix is composed of finer material (6.7%, Fig. 2). Boulders and large cobbles are
135 quite abundant, corresponding to an amount by volume of about 20% (resulting
136 from Image Processing of a Vertical Trench IPVT of the source area entrainable
137 material.

138 In the headwater basin, there are rock faces and talus slopes that continuously
139 recharge the catchment with new sediment. For this reason, we can consider the
140 Rudan torrent as a transport-limited system [14] in terms of sediment yield due to
141 debris flows. The most important source of sediment is the area named "Vallon
142 dell'Antelao" that is located between 2400 m a.s.l and 2000 m a.s.l (Fig. 1). This
143 zone is characterized by the highest terrain slope between the three basins (Tab. 1)
144 and is formed by a steep talus cone covered by loose debris, with a grain size that
145 varies from silt to boulders of 5 m in size. This area is clearly an unlimited source
146 of material, and the depth of the available sediment thickness has been evaluated
147 as more than 20 meters [40].

Table 1: Main characteristics of the three hydrological modelling areas.

	Rudan	Chiesa	Rebaixader
Area (km ²)	0.82	0.48	0.53
Max Elevation (m a.s.l)	3260	2503	2475
Min Elevation (m a.s.l)	1804	1692	1350
Mean Elevation (m a.s.l)	2507	2086	1738
Average terrain slope (°)	47	31	32
Average channel slope (°)	43	35	25

148 2.2. The Chiesa catchment

149 Chiesa is a torrent that flows down the south side of Col di Lana (2452 m
150 a.s.l.) (Fig. 3). This mountain is inside the dolomitic territory but is characterized
151 by a different geology than that of the Rudan basin. The hydrological modelling
152 area of this basin is the smallest between the three study areas (0.48 km², Tab. 1),
153 whereas the total area of the catchment is of 1.15 km² (red line in Fig. 3) with an
154 elevation range between 1180 and 2450 m a.s.l.. The mean annual precipitation
155 of the basin is 1080 mm and the mean number of rainy days per year is 114 (data
156 collected between 1985 and 2018 by the meteorological station of ARPAV – Re-
157 gional Agency for Environmental Prevention and Protection of Veneto – located
158 in Arabba, BL - WGS84 coordinates: 11.9° E, 46.5° N).

159 The main rock types consist of: (1) conglomerates, (2) volcanic rocks such
160 as hyaloclastites and tufas (Fernazza formation) and (3), especially, in the lower
161 part of the catchment, calciculites and limestones (Livinallongo formation) [42].
162 The soil composition in Chiesa basin is also different from that in the Rudan
163 catchment. The soil matrix in the source area is composed by a silt percentage

Figure 1: Map of the Rudan catchment with a zoom-in of the triggering area named “Vallon dell’Antelao”.

164 of 22.6% and clay percentage of 9.4% (Fig. 2) thus, percentage of the finest soil
 165 component is higher than that of the gravel and sand component. The cobble and
 166 boulder presence is rare, being approximately equal to 5% (resulting from IPVT).

167 The main channel of the basin is the Chiesa torrent, which flows into the
 168 Cordevole torrent at 1175 m a.s.l., passing through the village of Pieve di Livinal-
 169 longo (BL, North-Eastern Italy) (Fig. 3). Immediately upstream of the National
 170 Road 48 “Delle Dolomiti”, there is a filter check-dam with a storage basin (Fig.
 171 3).

172 The source areas where debris flows initiate are not surrounded by rock faces

Figure 2: Grain size of the soil matrix in the three hydrological modelling areas.

like in the Rudan basin. These areas are parts (mostly flanks) of landslides under accelerated erosion with a high slope gradient (approximately 35-45°). Here, rocks and sediments emerge from a matrix mainly composed of silt and sand (Fig. 2). Moreover, these triggering zones are not located exactly in the upper part of the catchment but are at an elevation from 1800 to 2100 m a.s.l. Above this elevation there is a flat zone, which partly disconnects [25] the highest part of the catchment from the debris flow-triggering areas. Although the morphology of the Chiesa catchment differs from that of the Rudan basin, this catchment can be considered a transport-limited system [14]. In fact, the high slope gradient and the abundant sediment cover are not limiting factors for debris-flow triggering.

2.3. The Rebaixader catchment

This catchment is located in the Spanish Pyrenees, near the border between the regions of Catalonia and Aragon (Fig. 4). The headwater basin area is relatively small (Tab. 1) and has an elevation range between 1350 and 2475 m a.s.l.. Whereas, the total area of the catchment is 0.7 km² with an elevation range between 1238 and 2298 m a.s.l.. The mean annual precipitation of the basin fluctuates between 1000 and 1500 mm.

Figure 3: Map of the Chiesa catchment with a zoom-in of the source areas

189 tuates between 800 mm and 1200 mm [43] and the mean number of rainy days
 190 per year is 152 (data collected by the meteorological station installed inside the
 191 catchment in 2009).

192 The transport zone of the Rebaixader catchment is relatively short (100-150
 193 m long, Fig. 4); the channel has a width of 8-10 m and a slope angle of 25° (Tab.
 194 1). In the lower part of the catchment, there is a small fan immediately before the
 195 intersection with the Noguera Ribagorçana River.

196 The debris-flow-triggering zone is a unique wide area characterized by a steep
 197 slope gradient (32°, Tab. 1) consisting of a lateral moraine with almost an un-

198 limited sediment supply (Fig. 4). The geology of this source area is composed
199 of metamorphic rocks; here, we can observe blocks of different dimensions, from
200 clay and silt to randomly sparse small/large boulders (about 15% by volume ac-
201 cording to IPVT). In this catchment, the composition of the matrix is similar to
202 the composition of the Rudan catchment matrix, i.e., the most abundant compo-
203 nents are gravel and sand, and only 2% of the matrix is silt and clay (Fig. 2). The
204 estimated depth of this sediment cover reaches up to tens of meters [44]. For this
205 reason, the catchment is often impacted by debris flow and debris flood events and
206 was selected to host a monitoring station. The great activity of this region allows
207 many data to be collected in a relatively short amount of time. The monitoring
208 station was installed in 2009, and since then, more than 30 debris flow and flood
209 events have been registered [45, 46, 36].

210 Similarly to the two other study areas, this catchment is a transport-limited
211 system [14], i.e. the limiting factor is the water input, whereas the slope gradient
212 and excess sediment recharge, with respect the debris flow generation, are always
213 above the critical thresholds.

214 **3. Data and methods**

215 The analysis of the triggering phenomenon in the three study areas has been
216 developed considering different triggering mechanisms. In particular, the two
217 main triggering mechanisms described in the literature are channel bed failure and
218 shallow slope failure [16]. We decided to distinguish between two more precise
219 subdivisions of the first type of mechanism: progressive bed erosion, when the
220 runoff generated by intense rainfall starts to erode the channel bed, and full bed
221 breakage, when there is an overall collapse of the channel bed and banks involving

Figure 4: Map of the Rebaixader catchment with a zoom-in of the triggering area.

222 blocks of higher dimensions than the previous subdivision.

223 Therefore, we considered the following three triggering scenarios:

- 224 1. In-channel triggering due to progressive bed erosion
- 225 2. Channel-bed failure due to full bed breakage
- 226 3. Shallow slope failure.

227 In Fig. 5 is represented the flow chart of the methodology used to study the

228 hydrology of the triggering areas, regarding in particular the first two scenarios.

229 In every catchment, we selected three control cross-sections in which we verified

230 at which conditions the critical discharge for the initiation of torrential flows was

231 exceeded (Figs. 6-7-8). To compute the critical water discharges in the control
232 cross-sections, for the first and second scenario, we used two different equations:
233 the equation proposed by [19] for the progressive erosion of the channel bed, and
234 the equation proposed by [47] for the bed breakage scenario. This second equa-
235 tion was developed to study the threshold destabilization slope of artificial block-
236 ramps (consolidation work built with boulders). The critical discharges obtained
237 with the second equation likely correspond to more powerful and destructive de-
238 bris flows after their initiation. The surges originating from these discharges have
239 the possibility to mobilize and transport blocks and boulders of high dimensions
240 even in the source area, leading to possible clogging mechanisms and deposit col-
241 lapses (dam-breaks) inside the channels.

242 For the third scenario, we conducted a slope stability analysis in the triggering
243 areas, using the geotechnical parameters of the soil to study the destabilization of
244 the hillslope due to water infiltration.

245 Considering the Rudan torrent, we analyzed the headwater basin both in terms
246 of hydrology and hillslope stability. Here, initiation zones are located at the foot
247 of steep rock faces [19] and are usually characterized by a very high slope gra-
248 dient and by the presence of loose and poorly cohesive debris that can be easily
249 mobilized by running waters. In the two other basins the triggering areas are not
250 properly located in the highest part of the catchment. In these cases the triggering
251 areas have been analysed (hydrology/hilloslope stability) considering the upslope
252 contributing area.

253 *3.1. The hydrological approach*

254 The aim of this part of the analysis was to identify the critical rainfall duration
255 related to the critical water discharge capable of mobilizing sediments, leading to

256 the triggering of a debris flow. First, in the three study areas, the headwater basin
257 and triggering areas of debris flow initiation were identified [48, 19].

258 In every hydrological modelling area (Fig. 1, Fig. 3 and Fig. 4), we se-
259 lected, inside the triggering areas, three cross-sections: two cross-sections along
260 the channel network and one cross-section in the corresponding outlet (Fig. 6,
261 Fig. 7 and Fig. 8). The xy coordinates of these sections and the thalweg slope in
262 the surrounding reach were extracted from the DTM (digital terrain model) maps
263 (DTM analysis in Fig. 5). In Fig. 6-7-8 it can be seen the morphology of the
264 cross sections extracted from the DTM maps. The slope of the thalweg profile
265 was calculated as the mean slope gradient in a close channel reach (cross-section
266 in the intermediate position) with a length of 30 m. To verify if the length used for
267 the slope computation of the reach influences the slope values and consequently
268 the critical discharge calculated with the selected equations, we also computed
269 the mean slope for reaches 10 m and 50 m long. The qualities of the topographic
270 bases used for the three basins were as follows: 1 m cell resolution for the Rudan
271 and Chiesa catchments and 0.5 m cell resolution for the Rebaixader catchment. In
272 Tab. 2, the width and bed slope (both in m/m and in degrees) of the cross-sections
273 are reported for a depth (y) of 1 m; this table also shows the mean grain size of the
274 active triggering zone measured using the pebble-count method sampled by line
275 (approximately 100 data samples).

276 Then, for every cross-section, we calculated the critical discharge per unit
277 width (q_c , m^2/s) related to the initiation of a debris flow surge (Fig. 5) using two
278 different equations:

- 279 1. The first one is the equation proposed by [19], that is as follows:

Table 2: Main parameters of the control cross-sections: d_m is the mean grain-size diameter of the considered triggering area, S is the mean hillslope gradient expressed in m/m, β is the hillslope gradient expressed in degrees, B is the section width and y is the related hydraulic depth.

	Rudan $d_m=0.15$ m			Chiesa $d_m=0.10$ m			Rebaixader $d_m=0.10$ m		
	Sec 1	Sec 2	Sec 3	Sec 1	Sec 2	Sec 3	Sec 1	Sec 2	Sec 3
S (m/m)	0.61	0.67	0.49	0.81	0.68	0.70	0.33	0.47	0.43
β (°)	31.38	33.82	26.10	39.01	34.22	34.99	18.33	25.14	23.11
B at $y=1$ m	3.51	6.18	11.5	9.10	9.31	5.44	7.56	11.61	5.51

$$q_c = 0.78 \frac{d_m^{1.5}}{\tan \beta^{1.27}} \quad (1)$$

Where d_m is the mean grain size (via the pebble-count method) of the terrain in the triggering zone (channel bed), and β is the mean hillslope gradient in the corresponding cross-section. For the Rudan and Chiesa catchments, the mean diameters (d_m) were measured during the surveys conducted for the construction of the two filter check-dams in the basins [41, 42]; whereas, for the Rebaixader catchment, the mean diameter was measured during a field survey in summer 2018.

2. The second equation used to calculate the critical discharge of every cross-section is the one proposed by [47]. This equation was developed to calculate the critical discharge capable of mobilizing sediments (mainly composed of granular material), causing the destabilization of artificial block-ramps (consolidation work built with boulders):

$$q_c = 0.257 (s - 1)^{0.5} g^{0.5} d_m^{1.5} \tan \beta^{-1.17} \quad (2)$$

Where, s is the ratio of the sediment density to the density of water, and g is the gravitational acceleration. In this formula, the calculation refers to the erosion of block-ramps with large blocks. Hence, we tested two different grain sizes ($d_m=0.3$ m and $d_m=0.5$ m) to give the corresponding discharge range for the destabilization of the sparse boulders present on the channel bed and banks inside the source area material.

After that, to calculate the critical water discharge Q (m^3/s) of every section, corresponding to the discharge per unit width calculated with Eqs. 1 and 2, we used a MATLAB computational code (MATLAB analysis in Fig. 5). This tool allows to analyze a cross section using as input: the Manning's roughness (n) and the xy coordinates of the section expressed in meters. The result is a table in which, for increasing values of flow height y (m) - from the bottom to the top of the section - the following parameters are shown: wet area A (m^2), width B (m), wet perimeter C (m), hydraulic radius R_h (m), flow velocity v (m/s), flow discharge Q (m^3/s), mean bed shear stress τ (N/m^2) and discharge per unit width q (m^2/s).

The stage-mean flow velocity relationship used by the MATLAB code to calculate water discharge (Q , m^3/s) is the turbulent uniform flow equation:

$$Q = A \frac{1}{n} (\sin \beta)^{0.5} R_h^{\frac{2}{3}} \quad (3)$$

where n is the Manning's roughness coefficient of the analyzed section. Based on literature findings for very low relative submergences (R_h divided by a reference coarse grain size) [49, 50] we assumed a Manning's n value of 0.1.

Whereas, the mean bed shear stress τ (N/m^2) is calculated using the Du Boys equation:

$$\tau = \gamma_w R_h \tan \beta \quad (4)$$

315 where γ_w is the specific weight of water (this is physically consistent because
316 we are considering the water runoff for the initiation of a debris flow and not a
317 mature debris flow wave).

318 For every cross section, in the resulting table from the MATLAB tool, we
319 searched for the q (m^2/s) values previously calculated with Eq.s 1 and 2 and we
320 extracted the corresponding Q (m^3/s) values (CRITICAL DISCHARGE step in
321 Fig. 5).

322 The application of Eqs. 1-2 has been done in the three cross sections to have a
323 global view of the headwater basin behavior. It is worth noting that Eq.s 1 and 2
324 are meaningful if they refer to a well confined flow at low flow stages. Therefore,
325 the critical threshold values obtained at Section 3 (hydrological modelling outlet,
326 see Section 3 in Figs. 6-7-8) are considered the most reliable, with a well confined
327 flow occurring here in all three basins.

328 To create the hyetographs to be used as input in the hydrological simulations,
329 we accounted for some empirical intensity-duration equations found in the liter-
330 ature. In particular, we chose between three intensity-duration equations already
331 used in other investigations: [29], [31] and [35]. To choose the equations that are
332 close to the typical rainfall events of each basin, we analyzed real rainfall events
333 associated with triggered debris flows.

334 The selection of the appropriate equation was carried out specifically for each
335 basin:

336 For the Rudan catchment, we simply calibrated the equation suggested by
337 [35]:

$$I_M = 21.0 D^{-0.55} \quad (5)$$

where I_M is the mean hourly intensity, and D is the duration. We chose this equation because [35] already used it in the determination of critical rainfall events for a dolomitic zone that includes our catchment.

For the Chiesa catchment, we selected five rainfall events that, over the last 20 years, have triggered torrential flows: 20/09/2000, 28/07/2003, 26/07/2006, 8/08/2015 and 04/07/2018. The rainfall data of the first four events were registered by the rain gauge of "Passo Falzarego", located about 4 km from the catchment, and the rainfall data of the last event (04/07/2018) was registered by a new rain gauge installed during 2017 inside the catchment area. For every rainfall event, we extracted the strongest rainfall burst, characterized by a minimum precipitation of 1 mm in 5 minutes. For every burst, we calculated the corresponding medium hourly intensity for different durations: 5, 10, 20, 30 and 60 minutes. We reported these values in a graph with the three intensity-duration equations from the literature (Fig. 9). The graph shows that the majority of the real bursts points are located near the equation of [29]:

$$I_M = 30.7 D^{-0.45} \quad (6)$$

For this reason, we chose this equation to create the hyetographs for the hydrological simulations.

For the Rebaixader catchment, we conducted a similar analysis using four triggering rainfall events: 11/07/2010, 27/06/2012, 4/07/2012 and 31/07/2015. The rainfall data of these events were registered by a rain gauge installed inside the catchment area [44]. We extracted the bursts of these events and compared

the points with the empirical equations (Fig. 9). In addition, for this case, we selected the equation of [29] as two events lie below and two events lie above this curve. Therefore, it seems this equation can, on average, better represent typical triggering rainfall events.

To create the input hyetographs for the hydrological simulations, we used four total rainfall durations: 15, 30, 60 and 120 minutes. Using Eqs. 5 and 6, we calculated the corresponding intensity for each rainfall duration (these were the analyzed intensities linked to the critical duration, which generated the exact debris-flow-triggering discharge at Section 3). Finally, using these intensity values, we created eight different input hyetographs with constant duration (see the example in grey at the right bottom of Fig. 5).

The rainfall-runoff simulations were conducted by means of the FLO-2D model [5]. FLO-2D is a bidimensional numerical model used to perform hydrologic-hydraulic simulations. Certified by FEMA (Federal Emergency Management, USA), FLO-2D is widely used to analyze the effects of floods on alluvial areas, fans, rivers and mountain torrents. The model works by means of the DTM maps of the analyzed basins. For each cell, the runoff propagation is calculated on the quadratic matrix composed by itself and the neighboring cells, which is possible in all eight directions. Two equations are used for the calculation of flow: the dynamic equation (Saint Vénant) and the equation of mass conservation. The main parameters that influence the results are: (1) the grid dimensions of the DTM cells used to create the floodplain, (2) the altitude, n -Manning (variable values from cell to cell) and mean catchment value of CN (curve number, [51]), and (3) the input hyetographs [5]. We used this model because it allows different types of hydrological simulations to be conducted using specific input parameters such as

Table 3: Percentages of the superficial extent of different land uses in the three headwater basins and the calculated mean CN values.

Rudan		Chiesa		Rebaixader	
Land type	Area (%)	Land type	Area (%)	Land type	Area (%)
Shrubs	4	Woods	32	Woods	75
Pastures	10	Pastures	56	Pastures	16
Scree	10	Scree	3	Scree	9
Rocks	76	Rocks	9		
Mean CN = 78		Mean CN = 75		Mean CN = 65	

the rainfall hyetograph and the detailed characteristics of the area at the spatial resolution of the DTM grid, enabling the immediate, simultaneous extraction of predicted runoff in different selected cross-sections. For the hydrological simulations, we used a mean unique CN for each basin, rather than a distributed CN, as the total size of the three catchments is low, and after verifying that the distributed CN assignment does not significantly change the results, particularly for strong rainfall events. Tab. 3 shows the different hydrological modelling areas and the corresponding mean CN values. The values agree with the CN assignments in comparable small mountain catchments where rainfall-runoff data were available for calibration [11].

Regarding the initial abstraction (infiltration and interception water losses at the beginning of the precipitation events), we used a value of 1 mm in all the simulations. Many authors have suggested that lower initial abstraction values give better simulation results than higher abstraction values in the case of steep slope catchments [19, 52, 53, 11].

We conducted the hydrological simulations, modelling the flood hydrographs

400 originating from the input hyetographs. We analyzed the resulting peak discharge
401 in each of the three control cross-sections (Figs. 6-7-8) to verify if the peak dis-
402 charge exceeded the critical discharge, which was previously calculated from Eqs.
403 1 and 2. Finally, we performed additional simulations, varying the rainfall event
404 duration until we found the exact rainfall duration corresponding to the critical
405 discharge for the mobilization of sediments in the studied channels.

406 The hydrological calibration of the simulations was not possible using real
407 flood hydrograph observations due to the low accessibility of the triggering ar-
408 eas and overall difficulty of gauging the flow rates in small, steep and unstable
409 channels. Therefore, to verify the influence of the mean CN value on the re-
410 sults, we performed additional simulations by varying the assignment of the mean
411 CN value, which was quoted approximatively for about 10% according to the find-
412 ings of [54]. The repeated simulations were then analysed to indicate the extent to
413 which our conclusions might be biased by the lack of a rainfall-runoff calibration.

414 3.2. *Slope stability approach*

415 To complete the analysis, we studied the slope stability of the triggering areas
416 using the geotechnical data of the soil. This second analysis allowed us to also
417 consider the second triggering mechanism, which is the mechanism related to the
418 potential hillslope instability, which can evolve into a shallow slope failure and
419 consequently into a debris flow.

420 Therefore, to consider the possibility that a debris flow will be triggered due to
421 a concurrent shallow landslide, we performed a stability analysis of the triggering
422 areas. The objective of this part focused on determining at which position of the
423 water table the hillslope nearby the triggering area becomes unstable or prone to
424 collapse [22]. To carry out this analysis, we first collected some samples of the soil

matrix in the triggering areas. Then, the geotechnical analyses were performed by professional laboratories to extract the soil characteristics (Tab. 4).

Using these characteristics, we conducted the infinite slope analysis of the three triggering areas, calculating the stability factor (FS) with the equation proposed by [55]:

$$FS = \frac{c' + (\gamma_s - m\gamma_w)z \cos \beta^2 \tan \phi}{\gamma_s z \cos \beta \sin \beta} \quad (7)$$

Where (see Tab. 4) c' is the effective cohesion, z is the height of the potential sliding plane, m is the water table parameter (the fraction of the z depth where the water table is located), β is the hillslope gradient, γ_s is the saturated soil unit weight and γ_w is the water unit weight (9.81 kN/m³). According to literature findings [56, 57] the debris flow occurs below the condition of full saturation of the bed and then the reliable m range has been taken not higher than 0.8. To assess β , we extracted the hillslope gradient of the zones right above the channel initiation points in the three source areas, measuring this gradient in a 50 m long segment. Therefore, these values are the average slopes of the triggering areas, and the real values might increase locally.

If the safety factor (FS) is greater than 1.0, the hillslope is stable, whereas, when FS approaches or is lower than 1.0, the hillslope becomes unstable, and the possibility of a shallow landslide exists.

4. Results

4.1. Results of the hydrological analysis

Regarding the results of the critical discharge analysis, Tab. 5 shows that the critical discharges per unit width obtained using the equation of [19] are generally

Table 4: Main geotechnical parameters resulting from the laboratory analysis of the soil matrix samples collected inside the three hydrological modelling areas.

	Rio Rudan*	Rio Chiesa*	Rio Rebaixader**
Saturated soil unit weight (γ_s) (kN/m ³)	17.52	17.98	17.70
Soil friction angle (ϕ') (°)	42.50	36.50	40.00
Effective Cohesion (c') (kPa)	10.00	12.00	4.00
Mean hillslope gradient (β) (°)	31	40	31

* GEODATA Laboratory (Ponte San Nicolò, Padova, Italy)

** Geomar and UPC Laboratory (Barcelona, Spain)

low (between 0.03 and 0.12 m²/s, Tab. 5). It is interesting that the value of τ_c for the Chiesa and Rebaixader catchments are very similar in terms of shear stress, whereas in the Rudan basin, these values are slightly higher (Tab. 5). Looking at Tab. 5 it can be noticed that we found a very narrow range of triggering discharges and shear stresses, which varies from 0.04 to 0.20 m³/s and from 272 to 413 N/m², respectively.

To verify the influence of the slope extraction on the resulting discharges we conducted a sensibility analysis in the three cross-sections at the basin outlets, using different reach lengths (10, 30 and 50 m) to extract the terrain slope. It has been verified that the unit critical discharge values only vary within a small range of -0.02 to +0.01 m²/s, meaning that the different reach lengths used for the slope extraction had a minimum influence on the calculated discharges.

Using the equation for block-ramps proposed by [47] with two different diameters (Tab. 6), the critical discharge is obviously higher because the runoff needed

461 for the mobilization of larger blocks is greater.

Table 5: Critical hydraulic parameters derived from [19] (Eq. 1) of the analyzed cross-sections. Values bold-italic are for the cross-sections at the hydrological modelling area outlet.

	Rudan			Chiesa			Rebaixader		
	Sec 1	Sec 2	<i>Sec 3</i>	Sec 1	Sec 2	<i>Sec 3</i>	Sec 1	Sec 2	<i>Sec 3</i>
q_c (m ² /s)	0.12	0.08	<i>0.09</i>	0.03	0.04	<i>0.04</i>	0.10	0.06	<i>0.07</i>
Q_c (m ³ /s)	0.19	0.13	<i>0.16</i>	0.02	0.04	<i>0.03</i>	0.20	0.10	<i>0.08</i>
τ_c (N/m ²)	353	358	<i>413</i>	272	263	<i>267</i>	282	288	<i>290</i>

462 The results (Tab. 7) demonstrate that the critical rainfall duration needed to
 463 reach the critical discharge for debris flow initiation (equation 1 of [19]) ranges
 464 between 12 and 22 minutes in the three basins. Moreover, the Rudan catchment
 465 shows the lowest rainfall intensity, while Chiesa catchment shows the highest and
 466 consequently is characterized by the minimum rainfall duration required to reach
 467 the critical value for the initiation of sediment mobilization (Tab. 6).

468 In Fig. 10, the hydrographs corresponding to Section 3 of the three catch-
 469 ments, located at the hydrological modelling area outlet, are shown. Among the
 470 three basins, the Rudan catchment is characterized by the highest critical dis-
 471 charge.

472 In the Rebaixader simulation area, the critical discharge corresponding to the
 473 possible triggering of debris flows is between the values of the two other basins
 474 (Tab. 5). Nevertheless, in this case, the rainfall duration needed to reach the
 475 critical discharge at the headwater basin outlet is very similar to that of Rudan
 476 headwater basin (Tab. 7) and the hydrograph resulting from the 15-minute rainfall
 477 duration is lower than the threshold (Fig. 10).

Table 6: Critical hydraulic parameters derived from [47] (Eq. 2, used for the erosion of block-ramps) of the analysed cross-sections, using the two diameters of 0.3 m (value before the slash) and of 0.5 m (value after the slash). Values in bold-italic are for the cross-sections at the hydrological modelling area outlets.

	Rudan			Chiesa			Rebaixader		
	Sec 1	Sec 2	<i>Sec 3</i>	Sec 1	Sec 2	<i>Sec 3</i>	Sec 1	Sec 2	<i>Sec 3</i>
q_c	0.27/	0.19/	<i>0.21/</i>	0.15/	0.19/	<i>0.18/</i>	0.41/	0.27/	<i>0.30/</i>
(m ² /s)	0.58	0.40	<i>0.45</i>	0.33	0.41	<i>0.39</i>	0.89	0.60	<i>0.65</i>
Q_c	0.47/	0.25/	<i>0.43/</i>	0.22/	0.58/	<i>0.29/</i>	1.59/	0.87/	<i>1.26/</i>
(m ³ /s)	1.74	1.34	<i>1.03</i>	0.85	2.62	<i>0.89</i>	4.08	2.32	<i>3.35</i>
τ_c	528/	455/	<i>662/</i>	660/	702/	<i>667/</i>	654/	670/	<i>663/</i>
(N/m ²)	925	945	<i>1050</i>	1073	1089	<i>1071</i>	1022	1048	<i>1040</i>

478 Considering the critical runoff discharge (Tab. 6) and shear stress values ob-
479 tained using Eq. 2 proposed by [47], we demonstrated a range of values triggering
480 more powerful and destructive debris flows, characterized by the overall collapse
481 of the torrent bed (involving blocks of great dimensions). In this case, the val-
482 ues required to reach these critical discharges are high and range for the outlet
483 section between 0.29 and 1.26 m³/s for $d_m=0.3$ m; in addition, hydrological sim-
484 ulations show that the rainfall duration needed for the mobilization of boulders in
485 the source area is between 30 and 60 minutes.

486 4.2. Results of the slope stability analysis

487 The slope stability analysis indicates that the Rudan and Rebaixader catch-
488 ments remain generally stable for important depths of the potential sliding plane
489 (Fig. 11). These basins show a hillslope terrain of approximately 31° and soil

Table 7: Main parameters of the hyetographs used for the FLO-2D hydrological simulations in the three basins and the corresponding peak discharges resulting from the simulations in the outlet cross-section (D_{tot} is the total duration, and P_{tot} is the total precipitation). In the last line, bold-italic values were obtained with the FLO-2D simulation, in which the resulting Q_{max} approaches the best the Q_c calculated with Eqs. 1 and 2.

Rudan				Chiesa				Rebaixader			
D_{tot}	P_{tot}	I	Q_{max}	D_{tot}	P_{tot}	I	Q_{max}	D_{tot}	P_{tot}	I	Q_{max}
(min)	(mm)	(mm/h)	(m ³ /s)	(min)	(mm)	(mm/h)	(m ³ /s)	(min)	(mm)	(mm/h)	(m ³ /s)
15	11.25	45.00	0.02	15	14.32	57.28	0.08	15	14.32	57.28	0.02
30	15.37	30.74	0.36	30	20.97	41.94	0.46	30	20.97	41.94	0.14
60	21.00	21.00	0.98	60	30.70	30.70	1.14	60	30.70	30.70	0.88
120	28.68	14.34	1.37	120	44.95	22.47	1.43	120	44.95	22.47	1.37
<i>22</i>	<i>13.36</i>	<i>36.43</i>	<i>0.13</i>	<i>12</i>	<i>12.61</i>	<i>63.05</i>	<i>0.04</i>	<i>22</i>	<i>17.68</i>	<i>48.21</i>	<i>0.07</i>

friction angle higher than 40° (Tab. 4); thus, the slope of the triggering areas are lower than the friction angle. In contrast, in the case of the Chiesa basin, the hillslope slope is approximately 40° , and the soil friction angle is 36.5° (Tab. 4). For this reason, as observed in Fig. 11, when the thickness of slipping approaches 2.5 meters (shallow landsliding), the hillslope becomes unstable, and the stability factor reaches the stability threshold, particularly for m values of approximately 0.8.

5. Discussion

For the first and second triggering mechanisms (i.e. bed failure due to progressive bed erosion and bed failure due to full bed breakage), considering the range of critical discharges resulting from Eq. 1 and Eq. 2, we can assume that this in-

501 terval includes the maximum probability for debris flow triggering. Our analysis
502 indicates that the critical discharge for the initiation of debris flow, as calculated
503 with Eq. 1, is generally low even accounting for different triggering locations and
504 geomorphological characteristics. Moreover, this discharge can be generated by
505 short and intense rainfall events with a duration between approximately 10 and 20
506 minutes if the rainfall intensity follows the threshold curves. The highest value of
507 critical discharge in the three study areas resulted in the Rudan catchment. This
508 higher value is likely derived from the larger channel width and coarser mean
509 diameter of the Rudan catchment than of the other areas and this is due to the
510 different geological characteristics of the study areas.

511 The maximum flow rates that we hydrologically identified with this approach
512 are comparable with the values measured in some dolomitic headwater basins
513 by [11]. The associated threshold intensities, which are provided by Eq.s 4-5
514 type curves, are undoubtedly a fundamental variable but a lower limit of their
515 duration resulted necessary to generate debris flows. This confirms that excess
516 infiltration overland flow plays a key role as it is supported by the agreement
517 between the hydrological CN-based simulations and the observed times of debris
518 flow triggering (Fig. 9).

519 Our results would not change significantly if all hydrological simulations were
520 repeated by considering the CN variation within an acceptable range of $\pm 10\%$.
521 For example, under this hypothesis, the critical duration needed to reach critical
522 discharge in section 3 of the Rebaixader catchment would vary in the interval of
523 18-30 minutes. In short, accounting for the acknowledgement on the CN hydro-
524 logical modelling, the selection of a CN value inside a $\pm 10\%$ interval is not a real
525 limitation, being the simulated flow-rates in an acceptable range of uncertainties.

526 Conversely, if the channel banks are characterized by the presence of blocks
527 with dimensions greater than 0.3 m at least partially armoring the bed bottom or
528 buried near to the bed surface (critical discharge of [47] calculated with Eq. 2),
529 a longer rainfall duration is needed for the mobilization of sediments, postponing
530 the triggering of high-intensity debris flow.

531 The outlet cross-section in each considered catchment does not show the high-
532 est critical discharge of the three selected sections. In the Rudan basin, the highest
533 critical discharge corresponds to cross-section 1, which is the section located in
534 the left channel inside the upper part of the source area. In the Chiesa basin, the
535 maximum critical discharge corresponds to cross-section 2, which is positioned in
536 the central part of the channel crossing the source area. Finally, in the Rebaixader
537 basin, the highest critical discharge corresponds to cross-section 1, which again
538 is located in the highest part of the source area. Therefore, it seems that gener-
539 ally, along the uppermost erosive paths inside the source areas, the critical runoff
540 needed for the mobilization of sediments is higher than that at the outlet section,
541 which is the weakest in terms of stability. This means that the rainfall intensities
542 and durations needed to destabilize these zones of the source areas are slightly
543 higher than those observed at the outlets of the hydrological modelling areas and
544 this behavior seems independent from the morphological and geological settings
545 of the basin. In conclusion, the zones more prone to a mobilization result to be
546 located at the toe of the source area as consequence of a combination of upslope
547 area (that is the rate of overland and/or channel flow) and local slope.

548 The maximum probability in terms of the necessary flow rate for debris-flow
549 initiation could be determined by selecting, for every triggering area, the maxi-
550 mum hazard values of different control cross-sections in which the process might

551 take place.

552 Moreover, the critical runoff discharge found in our study for the mobilization
553 of sediments is comparable to the discharge found by [58], who reported a value
554 of $0.15 \text{ m}^3/\text{s}$ for the in-channel runoff needed to start a debris flow; they also stated
555 that a high antecedent moisture level in the soil is not required for the debris flow
556 initiation. The behavior of the Rudan headwater basin can be compared to that
557 of the Chalk Cliffs catchment [58]; apparently, in this type of basin characterized
558 by sedimentary rocks and wide source areas surrounded by steep rock faces, debris
559 flows initiate because intense rainfall events fall on the rocky faces and couloirs,
560 generating critical runoff that abruptly mobilizes sediments located in the under-
561 lying talus cones. This typical triggering behavior has been already described by
562 various authors in recent years [18, 19, 59, 11], and our simulated hydrological be-
563 havior highlights the strong capacity of water to initiate the massive mobilization
564 of sediments on steep slopes. To protect populations living downstream of these
565 critical zones, it is important to understand this behavior: the high amount of ma-
566 terial stored in source areas, the generally low runoff discharge needed for the
567 mobilization of sediments and the frequency of intense and short thunderstorms
568 during summer [18, 40, 43, 60] make these areas strongly susceptible to debris
569 flows. From the perspective of population protection and based on our findings,
570 we suggest that the drainage and diversion of small discharges in the triggering
571 zones could provide great benefits in the reduction of debris flows in terms of
572 magnitude and frequency of occurrence.

573 The critical shear stresses resulting from the control cross-section analyses are
574 comparable among the three basins, meaning that similar erosive shear forces are
575 needed to mobilize the sediments inside the channels. Nevertheless, the Chiesa

576 and Rebaixader catchments, characterized by wide steep eroded hillslopes, show
577 slightly smaller critical shear stresses than the Rudan basin. The Rudan basin
578 is characterized by a steep talus cone rich in large boulders surrounded by rock
579 faces, and it seems that this morphology compared to the Chiesa and Rebaixader
580 morphologies requires increased stress to mobilize sediments in the channel bed.

581 The Rudan and Rebaixader catchments in particular are characterized by the
582 presence of big blocks in the triggering areas [61]. Therefore, the second dis-
583 charge initiation threshold derived with the formula of [47] assumes an important
584 relevance in the comprehension of both a second level of triggering mechanism
585 (i.e. full bed breakage) and the following overall dynamics after the first surge
586 formation. The mobilization of these big blocks is the consequence of a high
587 water discharge that could result in the generation of debris flows near the max-
588 imal values in terms of both flow peaks and total sediment volumes. Exceeding
589 this second flow rate threshold could confirm that the link between the amount
590 of debris flow-triggering precipitation and the debris flow volume is discontinu-
591 ous when linked with the macroscopic bimodal nature of grain size distribution
592 of the debris flow material (e.g., boulders and coarse cobbles immersed in a fine
593 matrix). Consequently, when full-bed breakage occurs, the debris flow volume
594 suddenly increases and/or a debris flood becomes debris flow [36].

595 Regarding the slope stability analysis [55], the water table is difficult to define
596 in the field, particularly in cases when no clear water table is distinguishable (e.g.,
597 the Rebaixader catchment). In these cases, the approaches using unsaturated soil
598 mechanics may yield more realistic results, but the uncertainty of such methods is
599 high because they require more geotechnical parameters (e.g. soil retention curve,
600 or Van Genuchten parameters) that are very difficult to assess with precision at

601 high steepness and locally variable conditions. Therefore, even if the suction may
602 play a certain role, we applied the infinite slope method in presence of water
603 table because the goal was an overall indication on the potential sliding of the
604 source area and the cross comparison with the other two mechanism of debris
605 flow occurrence.

606 Analysing Fig. 11 and considering a reference soil thicknesses for instability
607 (i.e. $z = 2.0$ m), the Chiesa catchment appears the nearest to the mechanism of
608 shallow slope failure [2], closely followed by the Rebaixader. When the m water
609 table parameter exceeds 0.5 (Fig. 11b, c) the hillslope condition becomes re-
610 ally close to the instability. Both basins differ from the Rudan basin being both
611 characterized by a poorly confined and lowly channelized source area. Chiesa
612 and Rebaixader basins seem generate debris flows dependent both on the partial
613 soil saturation and runoff concentration. On the contrary, the Rudan catchment
614 - the only source area bounded at the head by rocky cliffs incised by hydrologi-
615 cally converging faults - shows a higher hillslope stability (greater FS in Fig. 11a)
616 confirming that in a Dolomitic context (comparable with that of the Rudan) the
617 pure channel bed erosion and failure prevails. This might happen during rainfall
618 events because intensive bed erosion and full bed breackage anticipate the full
619 conditions of slope failure that in turn would require longer time. Thus at the
620 triggering, the channel bed and the surrounding hillslopes are quite far from soil
621 saturation ([57]; e.g. Fig. 11a, with $m = 0.5$) and the flow rate stressing the source
622 area and exceeding the threshold values represents the driving conditions for de-
623 bris flow initiation. The two different behaviours could be classified as ‘flow rate
624 dominant’ in the Rudan-type basins and ‘mixed (flow rate/slope stability)’ in the
625 Chiesa-Rebaixader type basins.

626 6. Conclusions

627 Considering the results obtained from this study, we can state that:

- 628 • Even if many intensity-duration curves are computed to determine the trig-
629 gering of debris flows, it seems that an additional minimum duration thresh-
630 old is needed, so that below this limit, the initiation of a debris flow is very
631 unlikely to occur.
- 632 • The critical rainfall duration associated with a high triggering probability
633 ranges between 12 and 22 minutes in the three study areas (basin areas
634 between 0.48 and 0.82 km²).
- 635 • The critical discharge needed to initiate a debris flow surge is generally low
636 (between 0.03 and 0.28 m³/s), meaning that a relatively low water runoff
637 at the outlet of the source area is needed to mobilize sediments inside the
638 channel and triggers debris flow phenomena.
- 639 • The critical discharge range derived from the two equations [47, 19] high-
640 lights the interval in which the debris flow triggering probability is higher.
641 In particular, in all the basins, a 60 minute rainfall with critical intensity is
642 capable of generating a water peak discharge exceeding the threshold for
643 the mobilization of boulders larger than 0.3 m (dam-break scenario). This
644 means that real rainfall events with similar characteristics can possibly trig-
645 ger torrential events where the magnitude order of debris flow volumes sud-
646 denly switches. This behaviour seems more probable in those catchments
647 whose source area is composed by abundant fine matrix coexisting with an
648 appreciable amount of boulders and large cobbles.

- 649 • The central parts of the source areas represent the zones that need the high-
650 est water discharge to be destabilized. This indicates that these reaches of
651 the gullies require a higher rainfall duration than other areas to initiate a
652 debris flow surge and that source area instability migrate from downstream
653 to upstream during an over-threshold rainfall event.
- 654 • The different catchment morphologies influence the main triggering mecha-
655 nism in addition to the 'basic' progressive bed erosion; therefore, in Rudan-
656 like basins, channel bed failure seems to be the dominant mechanism, whereas
657 in basins similar to Rebaixader and Chiesa, the shallow slope failure mecha-
658 nism or a mix between the two types of mechanisms is more likely to occur.

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664 **References**

- 665 [1] O. Hungr, S. Leroueil, L. Picarelli, The Varnes classification of landslide
666 types, an update, *Landslides* 11 (2) (2013) 167–194. doi:10.1007/s10346-
667 013-0436-y.
- 668 [2] D. Rickenmann, *Methods for the quantitative assessment of channel pro-*
669 *cesses in torrents (steep streams)*, CRC Press, Taylor and Francis Group,
670 Leiden, Netherlands, 2016.

- 671 [3] G. H. Eisbacher, Slope stability and Land Use in Mountain Valleys, Geo-
672 science Canada 9 (1) (1982) 14–27.
- 673 [4] S. Fuchs, R. Kaitna, C. Scheidl, J. Hübl, The Application of the Risk Con-
674 cept to Debris Flow Hazards, Geomechanik und Tunnelbau 1 (2) (2008)
675 120–129. doi:10.1002/geot.200800013.
- 676 [5] J. O’Brien, P. Julien, W. Fullerton, Two-Dimensional water flood and mud-
677 flow simulation, Journal of Hydraulic Engineering 119 (2) (1993) 24–261.
678 doi:10.1061/(ASCE)0733-9429(1993)119:2(244).
- 679 [6] A. Burton, J. C. Bathurst, Physically based modelling of shallow landslide
680 sediment yield at a catchment scale, Environmental Geology 35 (2-3) (1998)
681 89–99. doi:10.1007/s002540050296.
- 682 [7] G. B. Crosta, P. Frattini, Distributed modelling of shallow landslides trig-
683 gered by intense rainfall, Natural Hazards and Earth System Sciences 3 (1/2)
684 (2003) 81–93.
- 685 [8] A. Armanini, L. Fraccarollo, G. Rosatti, Two-dimensional simulation of de-
686bris flows in erodible channels, Computers and Geosciences 35 (5) (2009)
687 993–1006. doi:10.1016/j.cageo.2007.11.008.
- 688 [9] O. Hungr, S. McDougall, Two numerical models for landslide dy-
689namic analysis, Computers and Geosciences 35 (5) (2009) 978–992.
690 doi:10.1016/j.cageo.2007.12.003.
- 691 [10] P. Horton, M. Jaboyedoff, B. Rudaz, M. Zimmermann, Flow-R, a model
692 for susceptibility mapping of debris flows and other gravitational hazards at

- 693 a regional scale, *Natural Hazards and Earth System Science* 13 (4) (2013)
694 869–885. doi:10.5194/nhess-13-869-2013.
- 695 [11] C. Gregoret, M. Degetto, M. Bernard, G. Crucil, A. Pimazzoni, G. De Vido,
696 M. Berti, A. Simoni, S. Lanzoni, Runoff of small rocky headwater catch-
697 ments: Field observations and hydrological modeling, *Water Resources Re-*
698 *search* 52 (10) (2016) 8138–8158. doi:10.1002/2016WR018675.
- 699 [12] T. Takahashi, Estimation of potential debris flows and their hazardous zones;
700 soft countermeasures for a disaster, *Journal of Natural Disaster Science* 3 (1)
701 (1981) 57–89.
- 702 [13] D. Rickenmann, M. Zimmermann, The 1987 debris flows in Switzer-
703 land: documentation and analysis, *Geomorphology* 8 (2) (1993) 175–189.
704 doi:10.1016/0169-555X(93)90036-2.
- 705 [14] M. J. Bovis, M. Jakob, The role of debris supply conditions in predicting
706 debris flow activity, *Earth Surface Processes and Landforms* 24 (11) (1999)
707 1039–1054. doi:10.1002/(SICI)1096-9837(199910)24:11<1039::AID-
708 ESP29>3.0.CO;2-U.
- 709 [15] D. Brayshaw, M. A. Hassan, Debris flow initiation and sediment
710 recharge in gullies, *Geomorphology* 109 (3-4) (2009) 122–131.
711 doi:10.1016/j.geomorph.2009.02.021.
- 712 [16] C. Tognacca, G. R. Bezzola, Debris-flow initiation by channel-bed failure,
713 *Debris-Flow Hazards Mitigations, Mechanics, Prediction, and Assessment*
714 (1997) 44–53.

- 715 [17] S. H. Cannon, J. E. Gartner, M. G. Rupert, J. A. Michael, Emergency assess-
716 ment of debris-flow hazards from basins burned by the Grand Prix and Old
717 Fires of 2003, Southern California, Tech. Rep. 1072 (2004).
- 718 [18] M. Berti, A. Simoni, Experimental evidences and numerical modelling of
719 debris flow initiated by channel runoff, *Landslides* 2 (3) (2005) 171–182.
720 doi:10.1007/s10346-005-0062-4.
- 721 [19] C. Gregoretti, G. Dalla Fontana, The triggering of debris flow due to
722 channel-bed failure in some alpine headwater basins of the Dolomites: Anal-
723 yses of critical runoff, *Hydrological Processes* 22 (13) (2008) 2248–2263.
724 doi:10.1002/hyp.6821.
- 725 [20] J. A. Coe, D. A. Kinner, J. W. Godt, Initiation conditions for debris flows
726 generated by runoff at Chalk Cliffs, central Colorado, *Geomorphology* 96 (3-
727 4) (2008) 270–297. doi:10.1016/j.geomorph.2007.03.017.
- 728 [21] W. Wu, R. C. Sidle, A Distributed Slope Stability Model for Steep
729 Forested Basins, *Water Resources Research* 31 (8) (1995) 2097–2110.
730 doi:10.1029/95WR01136.
- 731 [22] R. M. Iverson, M. E. Reid, R. G. Lahusen, Debris flow mobilization from
732 landslides, *Annual Review of Earth Planetary Science* 25 (1997) 85–138.
733 doi:10.1146/annurev.earth.25.1.85.
- 734 [23] M. E. Reid, R. G. LaHusen, R. M. Iverson, Debris-Flow Initiation Experi-
735 ments Using Diverse Hydrologic Triggers, in: C. Cheng-Iung (Ed.), *Debris-
736 Flow Hazards Mitigation: Mechanics, Prediction and Assessment*, American

- 737 Society of Civil Engineers (ASCE), San Francisco, California, 1997, pp. 1–
738 11.
- 739 [24] N. Lu, J. Godt, Infinite slope stability under steady unsaturated
740 seepage conditions, *Water Resources Research* 44 (11) (2008) 1–13.
741 doi:10.1029/2008WR006976.
- 742 [25] M. Cavalli, S. Trevisani, F. Comiti, L. Marchi, Geomorphometric assessment
743 of spatial sediment connectivity in small Alpine catchments, *Geomorphol-*
744 *ogy* 188 (2013) 31–41. doi:10.1016/j.geomorph.2012.05.007.
- 745 [26] N. Caine, The rainfall intensity - Duration control of shallow landslides and
746 debris flows, *Geografiska Annaler. Series A, Physical Geography* 62 (1-2)
747 (1980) 23–27.
- 748 [27] J. Innes, Debris flows, *Progress in Physical Geography* 7 (4) (1983) 469–
749 501. doi:10.1177/030913338300700401.
- 750 [28] M. Moser, F. Hohensinn, Geotechnical aspects of soil slips in
751 Alpine regions, *Engineering Geology* 19 (3) (1983) 185–211.
752 doi:https://doi.org/10.1016/0013-7952(83)90003-0.
- 753 [29] S. H. Cannon, S. Ellen, Rainfall conditions for abundant debris avalanches,
754 San Francisco Bay region, California, *California Geology* 38 (12) (1985)
755 267–272.
- 756 [30] R. C. Wilson, G. F. Wieczorek, Rainfall Thresholds for the Initiation of
757 Debris Flows at La Honda, California, *Environmental & Engineering Geo-*
758 *science I* (1) (1995) 11–27. doi:https://doi.org/10.2113/gseegeosci.I.1.11.

- 759 [31] P. Paronuzzi, A. Cocolo, G. Garlatti, Eventi meteorici critici e debris flow
760 nei bacini montani del Friuli, *L'acqua* 6 (1) (1998) 39–50.
- 761 [32] A. M. Deganutti, L. Marchi, M. Arattano, Rainfall and debris-flow occur-
762 rence in the Moscardo basin (Italian Alps), in: G. F. Wieczorek, N. Naeser
763 (Eds.), *Debris flow Hazards Mitigation: Mechanics, Prediction, and Assess-*
764 *ment; Proceedings of the 2nd International DFHM Conference, Taipei, Tai-*
765 *wan, 2000*, pp. 67–72.
- 766 [33] G. Crosta, P. Frattini, Physically based distributed modelling for shallow
767 landslide Hazard Zonation, in: *Proceedings 3rd EGS Plinius Conference,*
768 *Baja, Sardinia, Italy, 2001*, pp. 463–487.
- 769 [34] M. Bacchini, A. Zannoni, Relations between rainfall and triggering of
770 debris-flow: case study of Cancia (Dolomites, Northeastern Italy), *Natural*
771 *Hazards and Earth System Science* 3 (1/2) (2003) 71–79. doi:10.5194/nhess-
772 3-71-2003.
- 773 [35] C. Gregoretti, G. Dalla Fontana, Rainfall threshold for the initiation of de-
774bris flows by channel-bed failure in the Dolomites, *Debris-Flow Hazards*
775 *Mitigation: Mechanics, Prediction, and Assessment* (2007) 11–21.
- 776 [36] R. Pastorello, M. Hürlimann, V. D'Agostino, Correlation between the rain-
777fall, sediment recharge, and triggering of torrential flows in the Rebaix-
778ader catchment (Pyrenees, Spain), *Landslides* 15 (10) (2018) 1921–1934.
779 doi:10.1007/s10346-018-1000-6.
- 780 [37] C. Gregoretti, The initiation of debris flow at high slopes: Experi-

- 781 mental results, *Journal of Hydraulic Research* 38 (2) (2000) 83–88.
782 doi:10.1080/00221680009498343.
- 783 [38] C. Tognacca, G. R. Bezzola, H.-E. Minor, Threshold criterion for debris-flow
784 initiation due to channel-bed failure, in: G. F. Wieczorek, Naeser (Eds.),
785 Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment,
786 2000, pp. 89–97.
- 787 [39] G. Blasone, M. Cavalli, L. Marchi, F. Cazorzi, Monitoring sediment source
788 areas in a debris-flow catchment using terrestrial laser scanning, *Catena* 123
789 (2014) 23–36. doi:10.1016/j.catena.2014.07.001.
- 790 [40] G. Bertoldi, V. D’Agostino, Colate detritiche: dinamiche degli apporti di
791 sedimento a scala integrata di bacino, Phd thesis, University of Padova
792 (2014).
- 793 [41] V. D’Agostino, M. Degetto, L. Marchi, D. Sonda, A. Vianello, Individ-
794 uazione e definizione delle soluzioni tecnico-realizzative maggiormente
795 idonee alla messa in sicurezza del torrente Rudan a ridosso dell’abitato di
796 Vodo di Cadore (loc. Peaio), Tech. rep., Associazione Italiana di Idronomia
797 AIDI (2002).
- 798 [42] V. D’Agostino, Progetto n° 647: Realizzazione di barriere fermaneve elas-
799 tiche e di opere di miglioramento del deflusso idraulico, Comune di Livinal-
800 longo del Col di Lana (BL), Tech. rep., Servizio Forestale Regionale Veneto,
801 Belluno (2003).
- 802 [43] C. Abancó, M. Hürlimann, J. Moya, M. Berenguer, Critical rainfall con-
803 ditions for the initiation of torrential flows. Results from the Rebaixader

- 804 catchment (Central Pyrenees), *Journal of Hydrology* 541 (2016) 218–229.
805 doi:10.1016/j.jhydrol.2016.01.019.
- 806 [44] M. Hürlimann, C. Abancó, J. Moya, I. Vilajosana, Results and experiences
807 gathered at the Rebaixader debris-flow monitoring site, Central Pyrenees,
808 Spain, *Landslides* 11 (6) (2014) 939–953. doi:10.1007/s10346-013-0452-y.
- 809 [45] M. Hürlimann, C. Abancó, J. Moya, C. Raïmat, R. Luis-Fonseca,
810 Debris-Flow Monitoring Stations in the Eastern Pyrenees. Description
811 of Instrumentation, First Experiences and Preliminary Results, *Ital-
812 ian Journal of Engineering Geology and Environment* (2011) 553–
813 562doi:10.4408/IJEGE.2011-03.B-061.
- 814 [46] C. Abancó, M. Hürlimann, Estimate of the debris-flow entrainment us-
815 ing field and topographical data, *Natural Hazards* 71 (1) (2014) 363–383.
816 doi:10.1007/s11069-013-0930-5.
- 817 [47] J. Whittaker, M. Jaggi, *Blockschwellen*, no. 91, Versuchsanstalt für Wasser-
818 bau, Hydrologie und Glaziologie, ETH, Zurich, Switzerland, 1986.
- 819 [48] M. Berti, R. Genevois, A. Simoni, P. R. Tecca, Field observations of a debris
820 flow event in the Dolomites, *Geomorphology* 29 (3-4) (1999) 265–274.
- 821 [49] J. C. Bathurst, Flow Resistance Estimation in Mountain Rivers, *Journal of
822 Hydraulic Engineering* 111 (4) (1985) 625–643.
- 823 [50] V. D’Agostino, T. Michelini, On kinematics and flow velocity prediction
824 in step-pool channels, *Water Resources Research* 51 (2015) 4650–4667.
825 doi:10.1002/2014WR016631.

- 826 [51] Soil Conservation Service, National Engineering Handbook (NEH4), tech-
827 nical report, Tech. rep., U.S. Department of Agriculture, Washington D.C.
828 (1972).
- 829 [52] R. H. Hawkins, T. J. Ward, E. Woodward, J. A. Van Mullem, Continuing
830 evolution of rainfall-runoff and the curve number precedent, 2nd Joint Fed-
831 eral Interagency Conference (2010) 2–12.
- 832 [53] F. D’Asaro, G. Grillone, Empirical Investigation of Curve Number Method
833 Parameters in the Mediterranean Area, *Journal of Hydrologic Engineering*
834 17 (10) (2012) 1141–1152. doi:10.1061/(ASCE)HE.1943-5584.0000570.
- 835 [54] D. Stewart, E. Canfield, R. Hawkins, Curve number determination meth-
836 ods and uncertainty in hydrologic soil groups from semiarid watershed data,
837 *Journal of Hydrologic Engineering* 17 (11) (2011) 1180–1187.
- 838 [55] T. Lambe, R. Whitman, *Soil Mechanics*, John Wiley & Sons, New York,
839 1968.
- 840 [56] F. Comiti, L. Marchi, P. Macconi, M. Arattano, G. Bertoldi, M. Borga,
841 F. Brardinoni, M. Cavalli, V. D’Agostino, D. Penna, J. I. Theule, A new
842 monitoring station for debris flows in the European Alps: first obser-
843 vations in the Gadria basin, *Natural Hazards* 73 (3) (2014) 1175–1198.
844 doi:10.1007/s11069-014-1088-5.
- 845 [57] R. Genevois, P. R. Tecca, M. Berti, A. Simoni, Pore pressure distribution
846 in the initiation area of a granular debris flow, in: E. Bromhead, N. Dixon,
847 M. Ibsen (Eds.), *Proceedings of the 8th International Symposium on Land-*
848 *slides*, no. 12, Cardiff, UK, 2000, pp. 615–620.

- 849 [58] J. A. Coe, S. H. Cannon, P. M. Santi, Introduction to the special is-
850 sue on debris flows initiated by runoff, erosion, and sediment entrain-
851 ment in western North America, *Geomorphology* 96 (2008) 247–249.
852 doi:10.1016/j.geomorph.2007.05.001.
- 853 [59] L. Marchi, G. Dalla Fontana, M. Cavalli, F. Tagliavini, Rocky Headwaters in
854 the Dolomites, Italy: Field Observations and Topographic Analysis, *Arctic,*
855 *Antarctic, and Alpine Research* 40 (4) (2008) 685–694. doi:10.1657/1523-
856 0430(07-037)[MARCHI]2.0.CO;2.
- 857 [60] F. Marra, E. I. Nikolopoulos, J. D. Creutin, M. Borga, Space-time organi-
858 zation of debris flows-triggering rainfall and its effect on the identification
859 of the rainfall threshold relationship, *Journal of Hydrology* 541 (2016) 246–
860 255. doi:10.1016/j.jhydrol.2015.10.010.
- 861 [61] M. Hürlimann, C. Abancó, J. Moya, Rockfalls detached from a lateral
862 moraine during spring season. 2010 and 2011 events observed at the Re-
863 baixader debris-flow monitoring site (Central Pyrenees, Spain), *Landslides*
864 9 (3) (2012) 385–393. doi:10.1007/s10346-011-0314-4.

Figure 5: Flow chart of the methodological steps followed to perform the hydrological analysis.

Figure 6: Location and shape of the three cross-sections of the Rudan hydrological modelling area.

Figure 7: Location and shape of the three cross-sections of the Chiesa hydrological modelling area.

Figure 8: Location and shape of the three cross-sections of the Rebaixader hydrological modelling area.

Figure 9: Comparison between the equations of [29], [31], [35] and: a) the five bursts that triggered debris flow in the Chiesa catchment; b) the four bursts that triggered debris flow in the Rebaixader catchment.

Figure 10: Hydrographs for the different simulated rainfall durations compared with the critical discharges for cross-section 3 of: a) Rudan, b) Chiesa, c) Rebaixader.

Figure 11: Stability factors for three possible water table height (m parameter in Eq. 7) in: a) Rudan, b) Chiesa, c) Rebaixader. The stability limit is $FS = 1$.