Assessments on debris flow distribution, triggering and evolution in the Dolomites area (North-Eastern Italy)

P.R. Tecca[1], R. Genevois[2], G. Scarso[2]

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

[2]Department of GeoSciences, University of Padova, Padova, Italy, rinaldogenevois@gmail.com

Abstract. Debris flows are considered among the most dangerous and destructive processes that affect mountainous areas all over the world. In Italy debris flows are very common in all the Alps, and in particular in the Dolomites (North-Eastern Italy). This paper concerns the study of debris flows distribution, triggering and evolution in the Cortina d'Ampezzo area, located in the Eastern Dolomites, sample study area over about 30 years in the context of National and European research projects. The morphology of the area is characterised by sub-vertical dolomitic cliffs and a thick talus developing from their base to the valley bottom. Through the analysis of aerial photographs, 325 debris flows, both channelized and hillslope type, have been detected. They all originate at the rock cliff base and develop towards the valley floor. The morphometric and hydrologic parameters of the rock headwater catchment and of the transport and deposition zones have been measured for each debris flow, as well as the recording of the rainfall responsible for the triggering process. The debris flows have been divided according to their type (hill-slope or channelized) and rock headwater catchments which do not give rise to debris flow have been considered separately. All the collected data have been statistically analysed getting some general conclusions especially regarding the headwaters that do not originate debris flows. The mean channel lengths increase over the years, and this would seem in connection with an increasing trend of total annual rainfall and frequency of maximum intensity since the late 1980s.

***Key words:** debris flow, morphometry, triggering mechanism, Dolomites (Italy)*

Cite this article: Tecca P.R., Genevois R., Scarso G. Assessments on debris flow distribution, triggering and evolution in the Dolomites area (North-Eastern Italy). In: Chernomorets S.S., Viskhadzhieva K.S. (eds.) Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 6th International Conference (Dushanbe–Khorog, Tajikistan). Volume 1. Dushanbe: "Promotion" LLC, 2020, p. 74–87.

Оценка масштабов распространения, механизмов возникновения и эволюции селевых потоков в районе Доломитовых Альп (Северо-Восточная Италия)

П.Р. Текка[1], Р. Женевуа, Дж. Скарсо[2]

[1]Исследовательский институт по гидрогеологической защите, Национальный совет по науке, Падуя, Италия

[2]Департамент наук о Земле, Падуанский университет, Падуя, Италия, rinaldo.genevois@unipd.it

Аннотация. Селевые потоки считаются одними из самых опасных и разрушительных процессов, затрагивающих горные районы во всем мире. В Италии селевые потоки очень распространены во всем Альпийском регионе, и, в частности, в Доломитовых Альпах (Северо-Восточная Италия). Настоящая работа посвящена изучению масштабов распространения, возникновения и эволюции селевых потоков в районе Кортина д'Ампеццо, расположенном в восточной части Доломитовых Альп, где в рамках национальных и европейских исследовательских проектов в течение примерно 30 лет проводились исследования. Морфология района характеризуется наличием субвертикальных, сложенных доломитами, скальных уступов и мощными осыпями, развивающимися от их подножия до днища долины. В результате анализа аэрофотоснимков было обнаружено 325 селевых потоков, как русловых, так и склоновых. Все они берут начало у основания скальных уступов и развиваются в направлении днища долины. Для каждого селевого потока были измерены морфометрические и гидрологические параметры всех частей водосборного бассейна: зоны зарождения, транзита и аккумуляции, а также собраны данные о количестве атмосферных осадков, выпадение которых стало триггером для схода селей. Селевые потоки были разделены в соответствии с их типом (склоновые или русловые), а водосборные бассейны, сложенные в верхних частях коренными породами и потому не подверженные сходу селевых потоков, рассматривались отдельно. Все собранные данные были статистически проанализированы, что позволило сделать некоторые общие выводы, особенно в отношении водосборов, не подверженных сходу селевых потоков. Средняя длина русел с годами увеличивается, и это, по-видимому, связано с тенденцией к увеличению общего годового количества осадков и частоты селей максимальной интенсивности с конца 1980-х гг.

Ключевые слова: *селевые потоки, морфометрия, триггерные механизмы, Доломитовые Альпы (Италия)*

Ссылка для цитирования: Текка П.Р., Женевуа Р., Скарсо Дж. Оценка масштабов распространения, механизмов возникновения и эволюции селевых потоков в районе Доломитовых Альп (Северо-Восточная Италия). В сб.: Селевые потоки: катастрофы, риск, прогноз, защита. Труды 6-й Международной конференции (Душанбе–Хорог, Таджикистан). Том 1. – Отв. ред. С.С. Черноморец, К.С. Висхаджиева. – Душанбе: ООО «Промоушн», 2020, с. 74–87.

Introduction

In the last years, increasing concern has been expressed about the state of the Alpine Environment and its safety, since European Alps play an important role in the economy and in the culture of the European countries. However, the means of defining, describing, monitoring and forecasting of the existing natural hazards should be considered not yet entirely adequate [*Armento,2007; Genevois et al., 2018*].

Debris flow hazards constitute one of the major threats to permanent settlements, tourist infrastructures as well as to transit routes. They occur, in facts, as sporadic, short, but severe events, mostly as a consequence of extreme hydro-meteorological conditions, conditioning the geomorphic evolution of the alpine torrent basins. Models of propagation and deposition of transported sediments and reliable mathematical and physical modelling have been developed [e.g. *Phillips and Davies, 1991; Coussot et al., 1998*], but they need to be fed by field or experimental parameters for an effective hazard mapping and a correct design of active defensive measures.

Apart from the use of numerical simulation models, hazard assessment is generally based on detailed classifications and mapping systems in order to identify factors contributing to the hazard and to assess dangerous processes. Everywhere is thus arising the need to control and to forecast debris flow hazards in order to mitigate related risk through a better understanding of the mechanics and dynamics of these processes [e.g. *Iverson, 1997; Berti et al., 2000; Tecca et al., 2003; Genevois and Tecca, 2016*]. These phenomena have, then, to be first described, their occurrence must be analysed and, finally, they have to be related to their consequences, that is defining three fundamental mapping stages: “danger, hazard and risk”.

In this paper only the initial level of mapping has been considered, excluding the assessment of risk and the management of the consequences. With the aim to detect the relevant characteristics of debris flows in the Cortina d’Ampezzo municipality (North-Eastern Italian Alps), characterized by numerous and frequent debris flows, morphometric parameters of existing debris flows have been measured through the examination of aerial photographs and adequate field check points. All the existing catchments have been analysed, setting the closure of headwater catchments at the base of the rock cliffs, where the scree slope can originate debris flows. Moreover, differentiation has been made between catchments originating or non-originating debris flows and between channelized and hill-slope debris flows.

For this purpose, basic information on geology, geomorphology, hydrology and hydrogeology of the area and the location of debris flows have been studied. Afterwards, the main geometrical and morphological characteristics have been statistically analysed and results correlated to rainfall intensity, as it is the only triggering factor in this study area.

Geological, geomorphological and climatic settings

The Cortina d'Ampezzo area is located in the Upper River Boite Valley (Eastern Dolomites, North-Eastern Alps). The stratigraphical sequence of sedimentary rocks outcropping in the whole dolomitic area includes lithologies from Upper Triassic to Lower Jurassic age (Fig. 1).

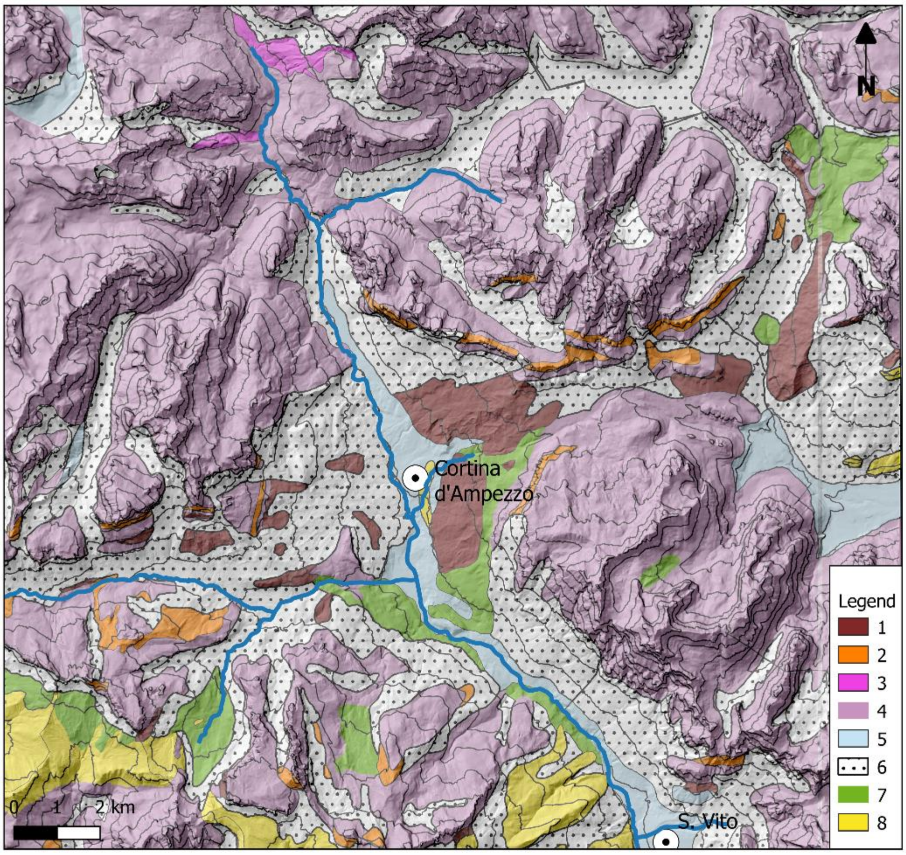

Fig. 1. Lithological sketch map of the Cortina d'Ampezzo area; 1: Alternation of sandstone and marl; 2) Mudstone and chalk; 3) Clayey limestone; 4) Limestone and dolomite; 5) Alluvial deposits; 6) Gravels; 7) Morainic deposits; 8) Vulcanites

Peak elevations vary between 2500 and 3200 m a.s.l., and valley floor has elevations ranging from 1100 and 1300 m a.s.l.. The morphology of the area is strongly influenced by the geological structure, mostly characterized by the presence of rigid over plastic formations. Rigid carbonate rocks (Dolomia Principale Fm.) built up high cliffs, whereas the pelitic formations (Raible Fm.) form gentler lower slopes. The dip of the stratigraphical units, generally upslope on the left River Boite side and downslope on the right one, imparted some asymmetry to the form of the main valley. On the left River Boite side, sub-vertical cliffs are present and the intense weathering has developed a thick talus. Slopes are widely covered by landslide deposits and scree of varying thickness, and the valley floor is blanketed by postglacial sediments and recent alluvial deposits [*APAT, 2009*].

The climatic conditions are typical of an Alpine environment. Annual precipitation roughly ranges from 900 to 1500 mm; precipitation mostly occurs as snowfall from November - December to April - May and as rainfall in late spring and summer, with a maximum between June and August (Fig. 2). To take into account the existing large differences in elevation, general rainfall distribution and rainy days have been considered for two of the four weather stations: the first one (Cortina, 1275 m a.s.l.) at the valley bottom, and the second one (Faloria, 2235 m a.s.l.) on a mountain top [*ARPAV, 2020*].

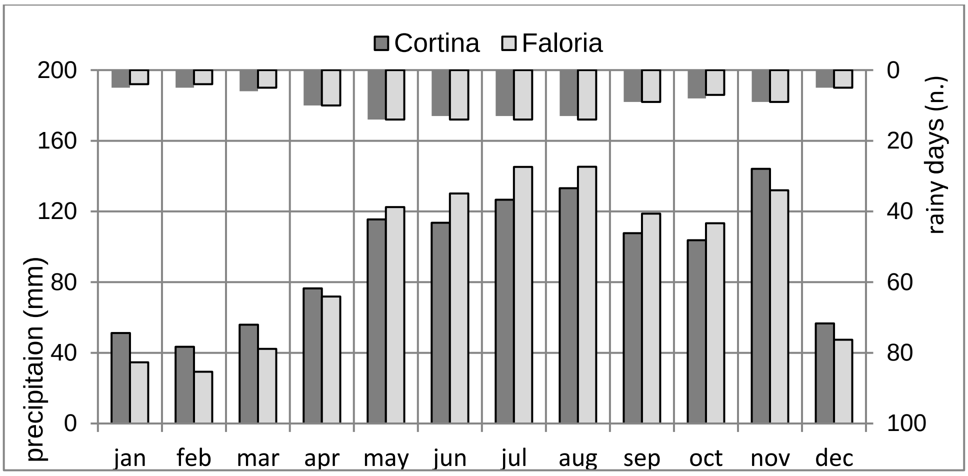

Fig. 2. Mean monthly precipitation and rainy days from 1982 – 2012 at Cortina d'Ampezzo (1275 m a.s.l.) and Faloria (2235 m a.s.l.) weather stations

Considering the mean monthly precipitation over the 1994-2019 period (Fig. 2), the differences between the two weather stations are limited, although the Faloria weather station, which is located at a higher elevation, displays higher values.

Due to the relevance of the rainfall intensity in the trigger mechanism, the rains of maximum intensity in time intervals of 5, 10 and 15 min were also considered. Cortina weather station shows a certain increasing trend of intensity precipitation, especially for the 10 min and 15 min time intervals (Fig. 3). For longer time intervals (30 min and 45 min), the increase of this trend is less pronounced.

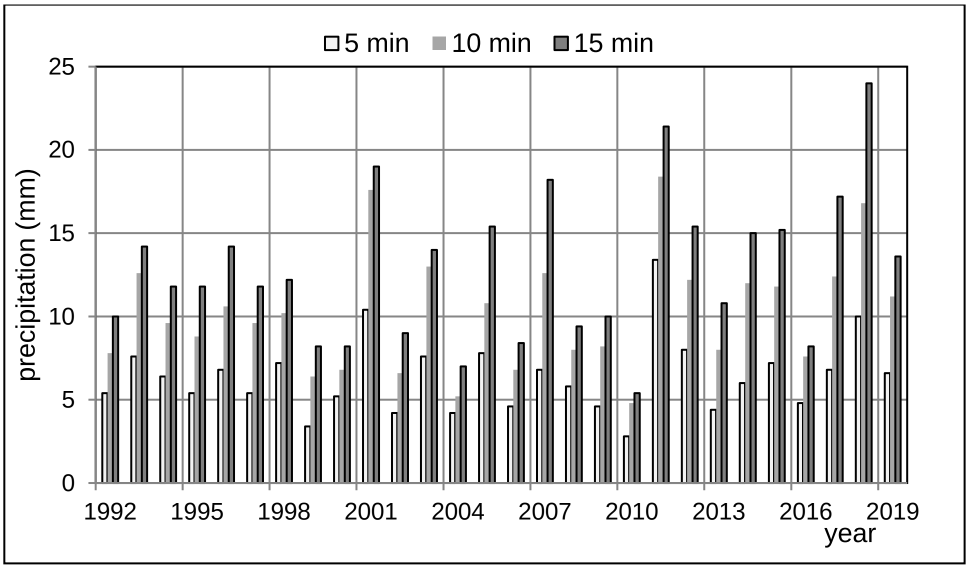

Fig. 3. Cortina weather station: precipitation intensity trend for the time intervals 5, 10 and 15 min

Debris flows distribution and characteristics

The most hazardous debris flows in the Cortina d'Ampezzo area are channelized debris flows, but many hillslope debris flows can be observed. The main characteristics of debris flows in the area were identified mainly from aerial photographs, implemented by field investigation. 191 hillslope and 133 channelized debris flows were identified out of a total of 324, and mapped (Fig. 4).

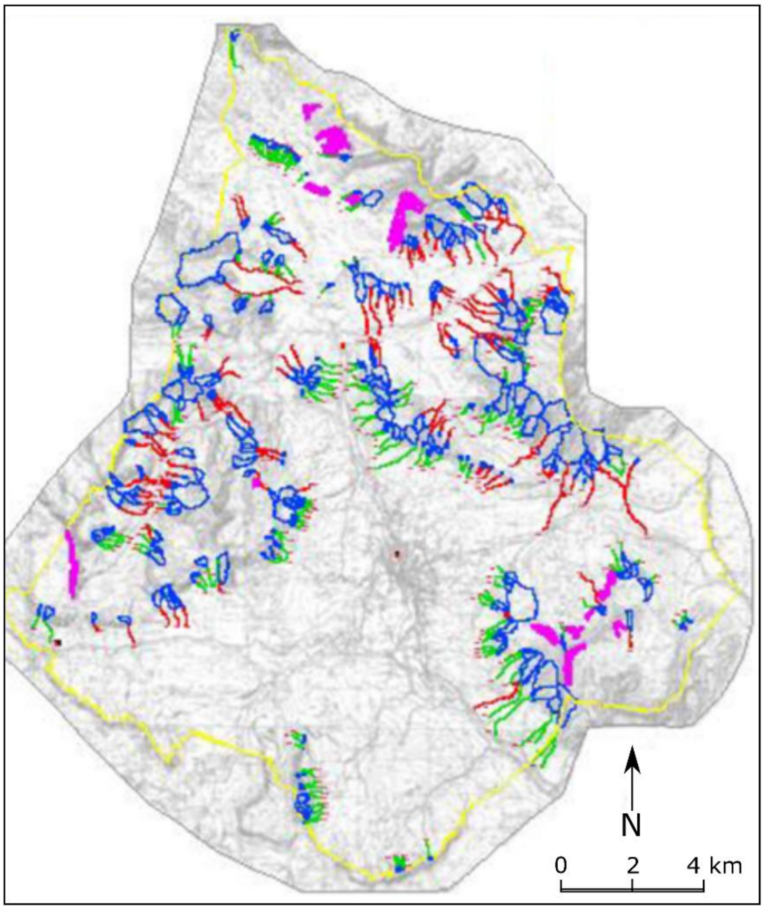

Fig. 4. Debris flow distribution in the Cortina d'Ampezzo area

Debris flows can be considered as the flow of a one-phase non-Newtonian fluid [*Pierson and Costa, 1987; Major and Pierson, 1990; Wang et al., 2014*]. Properties of transported material can be measured mostly in static condition, whereas only a few can be accurately measured in flowing debris. Many Authors report physical characteristics of these materials in the studied area [*e.g., Berti et al., 2000; Tecca et al., 2003; Berti and Simoni, 2005; Armento et al., 2008*].

The transported sediment is poorly sorted, containing up to 30% in weight of finer fraction (silts and clays). Typical mean values of main physical and mechanical parameters, determined on samples with particle diameter less than 20 mm, are: i) effective internal friction angle: 37°-44°; ii) void ratio: 0.31-0.36; iii) saturated density:1940-2200 kg/m^3. The comparison of the inferred field conditions with the "scaled" critical lines indicates a contractive behaviour of the in-situ material, then a high susceptibility of the material to liquefy at failure.

The basins were first discriminated in producing (DF) and not producing debris flows (NON-DF). Each DF, was then classified as hill slope (HS DF) or channelized (C DF), and the following morphometric parameters were assessed, by aerial photos analysis implemented by direct field surveys: 1) slope exposition; 2) basin: area, length and width, maximum and minimum elevation, form factor and time of concentration; 3) length of the flow channel for

NON-DF, calculated as the distance between the source area and the end of the deposition zone for DF; 4) mean slope of the transport, deposition and source area zones.

The form factor A_f, a dimensionless ratio of the basin area to the square of its length is always less than 0.79: the smaller its value the more the basin is elongated, that produces a low peak flow of longer duration. Basins with higher A_f values are characterized by high peak flow of shorter duration [*Farhan, 2017*]. The concentration time (t_c), the response of the watershed to a rainfall event, has been calculated with the *Kerby-Kirpich* method, applicable to watersheds ranging from about 0.65 to 388.km^2 [*Roussel et al., 2005*]. The total concentration time is obtained by adding the overland flow time (t_{ov}) to the channel flow time (t_{ch}):

$$t_c = t_{ov} + t_{ch}$$

Values of morphometric parameters of the catchments (area A and form factor A_f) and flow channels (length L, transport Tr. and deposition Dep. slopes) together with the hydrologic parameter (tc) were statistically analysed, obtaining the density histograms of each parameter value and the best distribution. An example for the lengths is shown in Fig. 5.

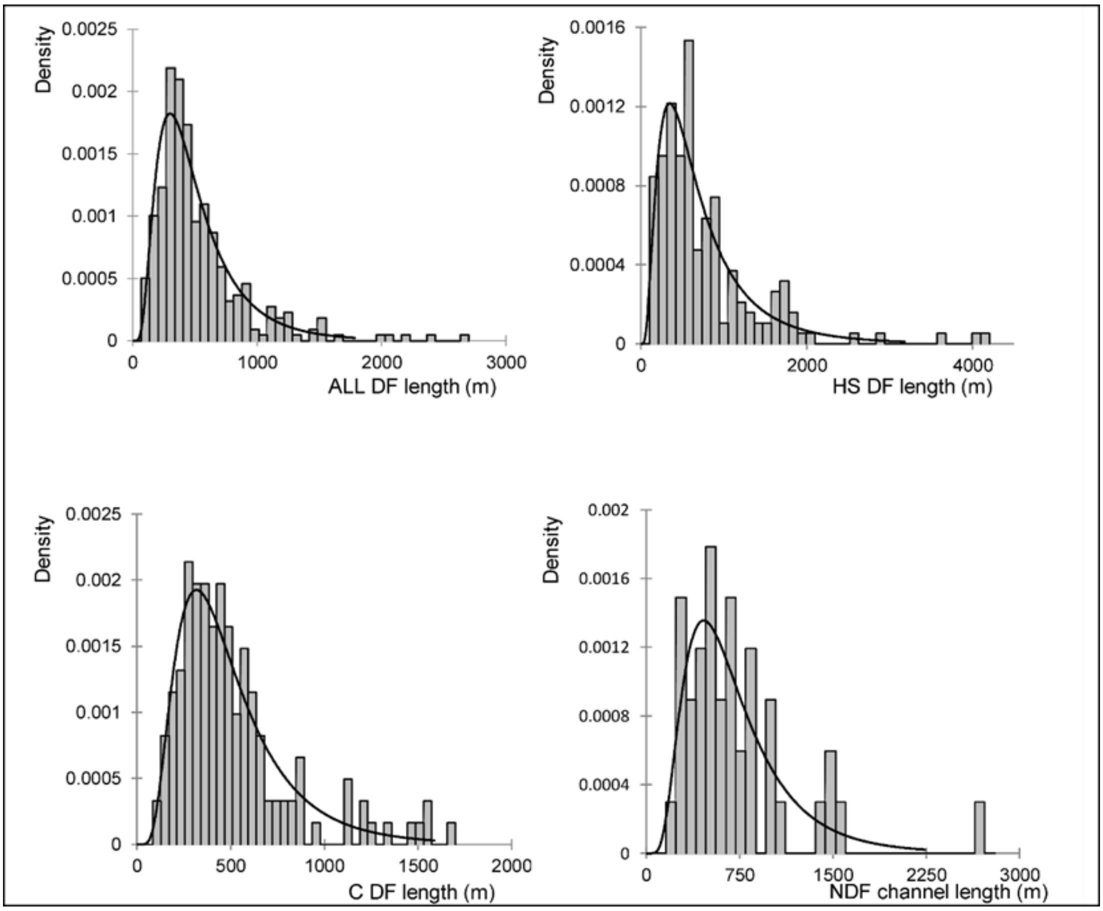

Fig. 5. Length histograms and best-fit log-normal distribution of the four types of basins

The statistical values of considered parameters for the four basin groups are shown in Table 1.

The log-normal distribution, generally significant in the description of natural phenomena, is almost always the best-fit distribution.

Assuming that the four basin groups can be considered statistical populations and the corresponding parameters are samples of these populations, a multiple comparison procedure has been performed using the *Kruskal-Wallis test*.

Table 1. Distribution parameters of morphological and hydrological characteristics of the basin groups

DF TYPE	No.	Distribution parameters	A (m^2)	A_f (--)	t_c (min)	L (m)	Tr. (°)	Dep. (°)
ALL DF	325	normal						
		μ	67696	0.190	6.24	524	29.2	23.5
		σ	106292	0.096	2.66	371	6.5	9.2
		log-normal						
		μ	10.212	-1.777	1.747	6.070	3.345	3.077
		σ	1.375	0.492	0.410	0.608	0.260	0.018
HS DF	182	normal						
		μ	53444	0.184	5.77	770	28.9	25.0
		σ	93635	0.089	2.29	651	7.4	9.4
		log-normal						
		μ	10.013	-1.806	1.681	6.378	3.325	3.150
		σ	1.307	0.485	0.377	0.725	0.303	0.391
C DF	143	normal						
		μ	85183	0.210	6.64	509	29.7	20.7
		σ	118119	0.139	2.75	316	5.0	7.2
		log-normal						
		μ	10.448	-1.714	1.807	6.072	3.375	2.965
		σ	1.427	0.030	0.419	0.558	0.185	0.379
NON DF	42	normal						
		μ	143206	0.182	11.15	730	–	–
		σ	221842	0.049	5.37	468	–	–
		log-normal						
		μ	11.133	-1.737	2.316	6.435	–	–
		σ	1.188	0.249	0.430	0.549	–	–

No.: number of observations; A: basin area; A_f: basin form factor; t_c: concentration time; L: flow channel length; Tr: transport area slope; Dep: deposition area slope.

The *Kruskal-Wallis* is a non-parametric test to compare outcomes among three or more independent groups when the assumption of normality cannot be accepted. In this test, if even one of the samples is different from another, the approximated probability value (p-value) will be lower than the considered significance level (5%) and the null hypothesis H_0 (the samples come from the same population) has to be rejected.

The analysis of the four basin groups shows that the null hypothesis H_0 has to be always rejected, but no significant differences between distributions result if form factor (A_f), transport slope (Tr) and, partially, deposition slope (Dep) are considered (Table 2).

Table 2. Results of the *Kruskal-Wallis test*

		ALL DF	HS DF	C DF	NON DF
A	ALL DF		No	No	Yes
	HS DF	No		Yes	Yes
	C DF	No	Yes		Yes
	NDF	Yes	Yes	Yes	
A_f	ALL DF		No	No	No
	HS DF	No		No	No
	C DF	No	No		No
	NDF	No	No	No	

		ALL DF	**HS DF**	**C DF**	**NON DF**
t_c	ALL DF		No	No	Yes
	HS DF	No		Yes	Yes
	C DF	No	Yes		Yes
	NDF	Yes	Yes	Yes	
L	ALL DF		Yes	No	yes
	HS DF	Yes		Yes	No
	C DF	No	Yes		Yes
	NDF	yes	No	Yes	
Tr.	ALL DF		No	No	
	HS DF	No		No	
	C DF	No	No		
Dep.	ALL DF		No	Yes	
	HS DF	No		Yes	
	C DF	Yes	Yes		

The most responsible parameters for the differences obtained have been identified through the *Kolmogorov–Smirnov test*, sensitive to differences in both location and shape of the empirical cumulative distribution functions. The test quantifies the maximum difference (D) between two cumulative distributions: the closer is D to 0, the more likely the two samples are drawn from the same distribution. The results, presented in Table 3, show that the D values are almost always equal or very close to 1 (> 0.9), suggesting that samples were not drawn from the same distribution. However, it should be noted that for the samples of transport slope (Tr) and deposition slope (Dep), the D value is considerably lower and therefore, the possibility that they come from the same distribution may not be completely excluded.

The correlations between geomorphological evolution of the slopes and the debris flow events have been explored analysing ten series of aerial photos, covering a time interval of 61 years. The data relating to the delimitation of the headwater catchments and the debris flow channels not reaching the valley bottom, have been entered, scaled and georeferenced so that they could be superimposed. Lengths were assessed in order to obtain an average elongation rate of the channels during the years.

Table 3. D values resulting from the *Kolmogorov–Smirnov tests*

		A	**A_f**	**t_c**	**L**	**Tr**	**Dep**
ALL DF	A		1	1	0.985	1	1
	Af	1		1	1	1	1
	tc	1	1		1	0.972	0.912
	L	0.985	1	1		1	0.994
	Tr	1	1	0.972	1		0.415
	Dep	1	1	0.912	0.994	0.415	
HS DF	A		1	1	0.967	1	1
	Af	1		1	1	1	1
	tc	1	1		1	0.972	0.952
	L	0.967	1	1		1	1

		A	A_f	t_c	L	Tr	Dep
	Tr	1	1	0.972	1		0.269
	Dep	1	1	0.952	1	0.269	
C DF	A		1	1	0.993	1	1
	Af	1		1	1	1	1
	tc	1	1		1	0.993	0.91
	L	0.993	1	1		1	1
	Tr	1	1	0.993	1		0.647
	Dep	1	1	0.913	1	0.647	
NON DF	A		1	1	1	----	----
	Af	1		1	1	----	----
	tc	1	1		1	----	----
	L	1	1	1		----	----

The results show a non-uniform annual increase in the average length of the channels, characterized by increasing velocity and acceleration. The best-fit line to experimental data (Fig. 6) is a third degree polynomial curve (R^2=0.9935) whose first derivative, that is the velocity of the annual channel elongation, shows an increase slightly exponential (R^2=0.9991), that can be really approximated to a linear regression (R^2=0.9988). Also the second derivative with respect to time, that is the instantaneous acceleration of the annual channel elongation, shows an exponential behaviour (R^2=0.8830), corresponding to an exact linear behaviour of the best-fit curve (R^2=1). The experimental data indicate a constant increase of the acceleration of channel elongation.

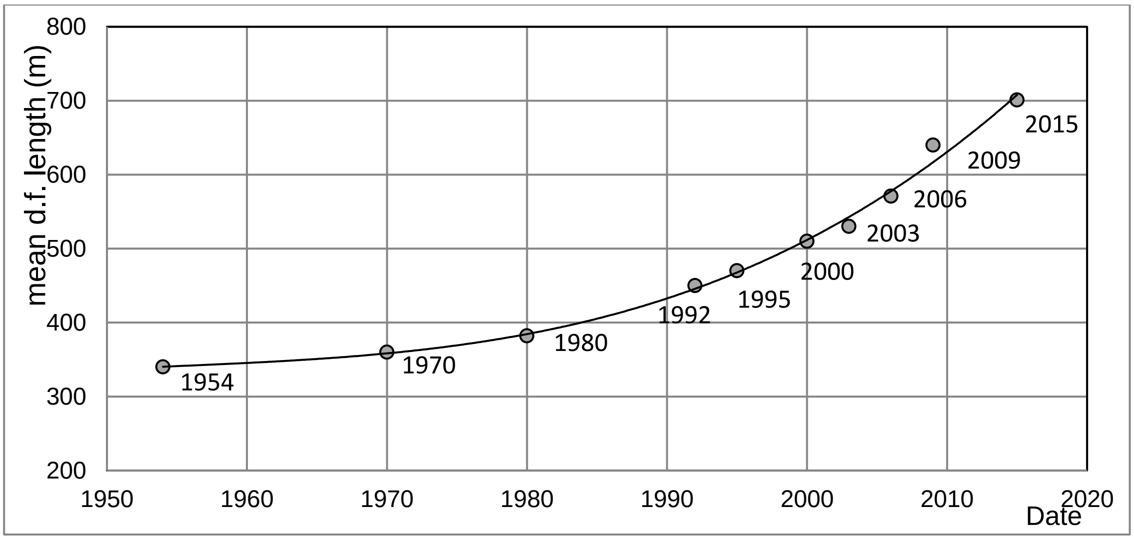

Fig. 6. Flow channels elongation evaluated by air photo interpretation.

Rainfall analysis

Rainfall in the study area have been analysed considering the annual precipitations registered at the four exiting weather stations in the period 1994-2019. Mean (μ) and standard deviation (σ) values of rainfall and rainy days are quoted in Table 4.

We analysed rainfall intensity data of the weather stations located in the Cortina d’Ampezzo area at different elevations (Faloria, 2235 m a.s.l.; Misurina, 1743 m a.s.l.; Podestagno, 1316 m a.s.l.; Cortina, 1271 m a.s.l.).

Table 4. Rainfall data in the study area

Weather station	Elevation (m a.s.l.)	Rainfall (mm)		Rainy days (mm)	
		mean (μ)	st. dev. (σ)	mean (μ)	st. dev. (σ)
Cortina	1271	1128.1	244.6	110	13.8
Podestagno	1316	1286.4	250.8	116	13.1
Misurina	1743	1180.9	181.1	117	10.6
Faloria	2235	1132.6	237.5	108	15.1

The maximum rainfall depths in short periods, registered in the period 1985-2019, have been preliminarily considered as a whole. Almost 200 events have been found with rainfall intensity ranging from 41 mm/30 min to 22 mm/6 min, but very intense precipitations were not common. Rainfall depths have then been analysed considering the elevation of the weather station, the chosen storm duration or time base T (5, 10 and 15 min) and the return period R (2, 5, 10 and 20 years).

As storm rainfall has been recognized since long time to be variable in space, the annual maxima of each chosen storm duration have been preliminarily compared with the Krustall-Wallis test. No significant statistical differences have been found, so the data of all stations have been taken into consideration for the definition of the critical rainfall with respect to debris flows initiation. A general very slight and irregular decrease of the rainfall depth (H) can be observed with the increase of the elevation for all the given storm duration (Fig. 7). Considering the weather stations with the higher elevation difference (Cortina, 1271 m a.s.l. and Faloria, 2235 m a.s.l.), the H annual maxima for the most significant return periods (R = 5, 10, 15 min), exhibit a power law behaviour (Fig. 8), confirming that rainfall depth, beside the considered storm duration, depends enough on the elevation of the weather station.

In order to have a better understanding of the effect of elevation on maximum intensity rainfall in the area, three rain gauges were located along a debris flow channel, 1.6 km long at the base of the rock cliff (1720 m a.s.l.), in an intermediate position (1494 m a.s.l.) and at the end of the channel, before the deposition area (1214 m a.s.l.); data were collected throughout 2016.

Increasing the time base used for the analysis from 1 min to 5 days, a general but not uniform decrease of the rainfall intensities can be observed: up to about 30 min time base rainfall intensities increase from the downslope to the upslope rain gauge showing differences that tend correspondingly to decrease. When time base is longer than 30 min (Fig. 9), significant differences do not exist.

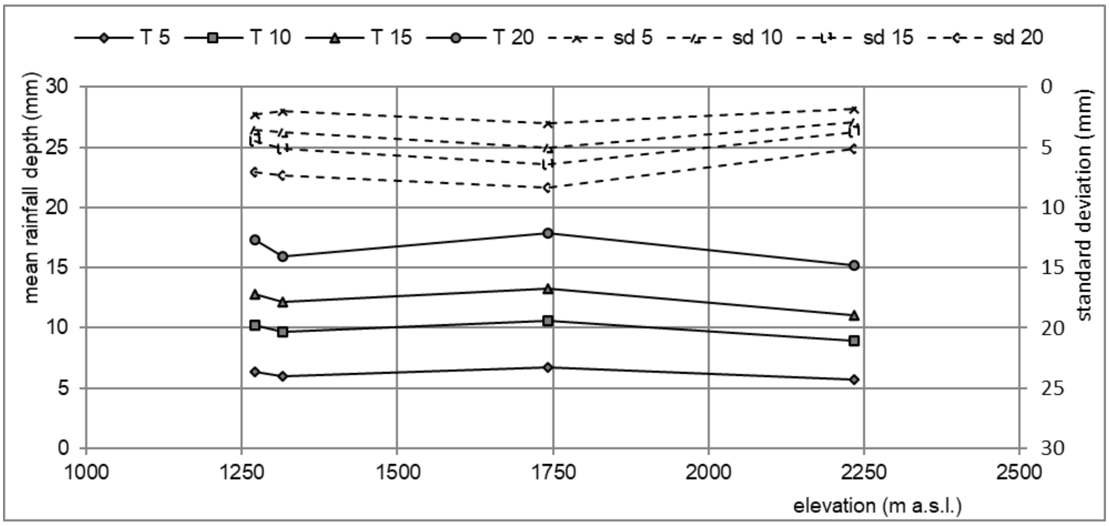

Fig. 7. Variation of mean annual maximum rainfall and corresponding standard deviation (sd, mm) with the elevation for different storm duration (T, mm)

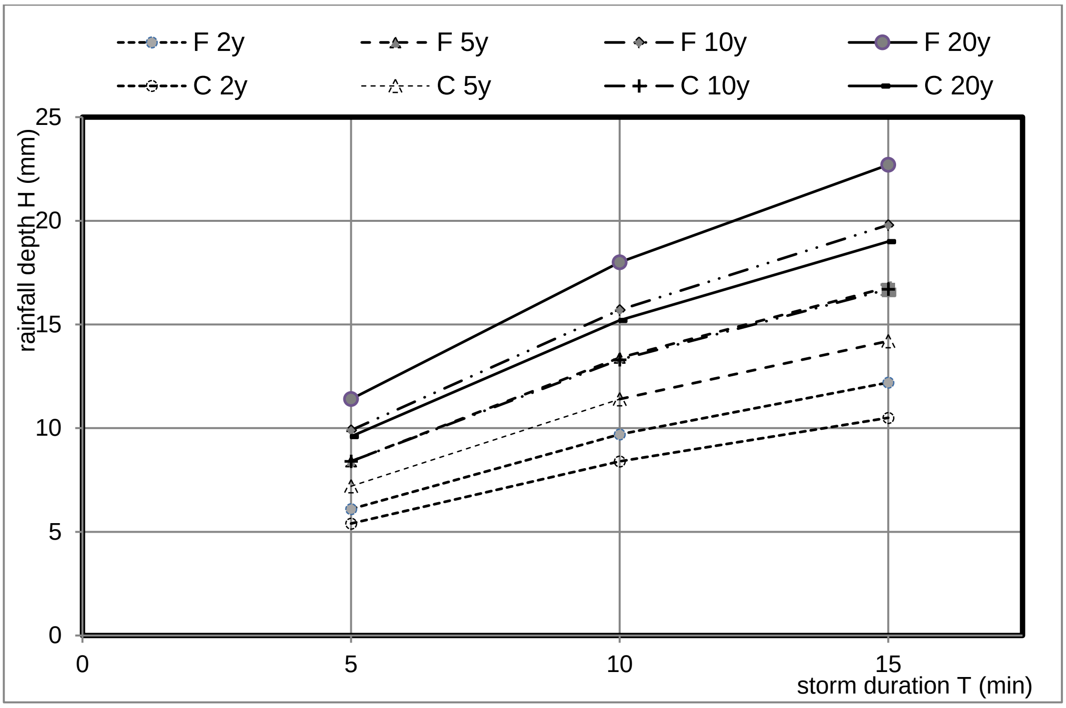

Fig. 8. Rainfall depth (H) vs storm duration (T) for 2, 5, 10 and 20 years return periods (weather station Faloria (F) and Cortina (C)

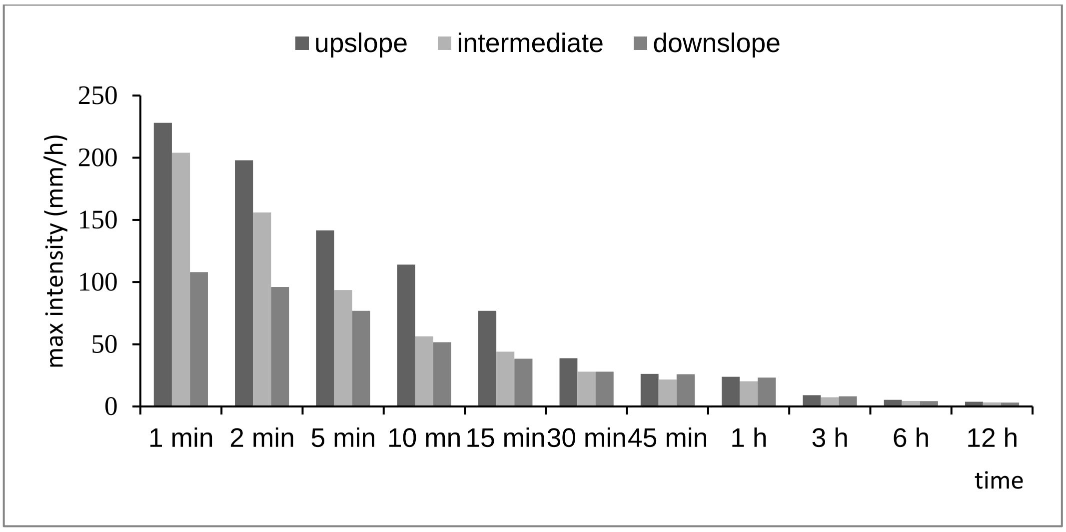

Fig. 9. Maximum rainfall intensities, at the downslope, intermediate and upslope rain gauges obtained with different time bases from April 22 to October 9, 2016

Discussion and conclusions

In order to find possible relationships between main geomorphic and hydrologic parameters of debris flows, we chose the sample area of Cortina d'Ampezzo (North-eastern Italy), having a large number of sediment source areas, lithologically homogeneous, producing both channelized and hill-slope debris flows. Geomorphic (length, transport and deposition gradients, headwater area and form factor) and hydrologic (rainfall and concentration time) parameters, evaluated by field investigation, air photo interpretation, and topographical maps, were then statistically evaluated and compared.

Ultimately, the comparison of the four considered statistical population (ALL DF, HS DF, C DF and NON-DF) shows that all distributions result statistically different. For a better understanding of the relationships between the given parameters, all possible pairs were then subsequently compared, using the *Kolmogorov–Smirnov test*. The results indicate that the distributions of the samples pairs are always different but, if mean values of parameters were also considered, some general conclusions can be drawn in particular as regards watershed that produce (ALL DF) or do not produce (NON-DF) debris flows. Indeed, mean values of basin area, concentration time and channel flow length of NON-DF watersheds are always greater than those obtained for ALL DF watersheds. However, while the flow channel length is directly connected to the morphological characteristics of the valley (depth and width), watershed area and concentration time seem to indicate different hydraulic triggering conditions.

Since debris flows occur in gullies eroded into very thick unconsolidated Quaternary deposits and, then, sediments availability can be considered unlimited, it can be said that their occurrence probability is a function mainly of the hydro-meteorological threshold exceeding. For a debris flow to occur, are needed both large quantities of water and high-intensity hydrodynamic forces in order to initially saturate sediments in the higher and steeper part of the gully. The consequent increase of pore water pressure lead to failure and the transformation of the solid mass of sediments into a debris flow. This condition depends on the relation between the rate of the entering water flow into sediments and the effective soil flow rate, that is in turn function of the hydraulic conductivity (k). Since involved sediments are characterized by very high k values (in the order of 10^{-1} - 10^{-3} m/s), and the source areas are rather steep (μ=37.1°and σ=8.1°), the amount of entering water flow should be very significant.

The water inflow depends mainly on: (a) basin size; (b) basin shape; (c) the rainfall intensity; (d) the time of concentration (t_c). Taking into account these facts, the triggering and the mobilization of debris flows can only occur during very heavy short periods rainfall.

Because debris flows in the Cortina d'Ampezzo area appear to be initiated largely by overland flow processes and, in particular, by the "firehose effect", the increase of pore water pressure derives mainly from the sudden impact of a water flow, a condition that can only occur during short-lasting heavy rainfall in small catchments with short concentration times. Consequently, in NON-DF watersheds, showing concentration times higher than ALL DF basins, it is presumable that the hydrodynamic forces necessary for the failure and the mobilization of the sediments cannot be developed [*Iverson, 1997; Marchi and D'Agostino, 2004*].

Since sufficient kinetic energy and excess pore pressures are required to maintain the flow condition, any decrease in the slope angle will decrease the debris flow mobility until the start of the deposition process. However, excess pore pressure dissipates mainly in the post-depositional consolidation phase [*Major and Iverson, 1999*] and, consequently, the deposition process would originate only from friction inside and at the edge of the flowing mass, where high pore pressure cannot completely develop. The same granular temperature, generated and maintained by the incessant conversion of bulk kinetic energy to grain fluctuation energy, may be considered function of the slope angle. The deposition process, then, is rather complicated but, simplifying, it will exist only one slope angle for which a cohesionless mass, with a particular friction angle and density, might mobilize in accordance with the Mohr- Coulomb failure criterion. Considering the range of both slope angles and present soil friction angle, the above considerations could explain the small differences observed between cumulative distributions of transport and deposition slope angles.

However, while mean values of transport slope gradient for HS DF and C DF are very similar (respectively 28.9° and 29.6°), mean values of deposition slope angle result greater for HS DF than for C DF (respectively 25.0° and 20.6°). Actually, it should be considered that the slope angle of the transport area depends greatly, in addition to the glacial morphology of the valley, on the frictional resistance of the detrital cover in the absence of a shallow groundwater. On the other hand, deposition slope angle depends, above all, on the rheological characteristics of the debris flow. Flume investigations on debris flow mixtures demonstrated that their behaviour changes also for small variations in concentration, kinetic energy content and grain size distribution, especially the clay content. Deposition will mainly occur when kinetic energy degrades and granular temperature falls to zero [*Major and. Pierson, 1992; Iverson, 1997*].

The dependence between the rheological parameters and the solid concentration has been investigated by many authors [*e.g., Phillips and Davies, 1991; Coussot et al, 1998; Martino,* *2003; GDR MiDi, 2004*]: they basically found that higher solid volumetric concentrations tend to decrease the bulk flow velocity (mobility) of the debris flow and that even relatively small variations of the water content strongly influence the viscosity and, then, the flow velocity to which deposition area shape, especially its length, are related.

The basins that originate or do not originate debris flows differ only for the value of the concentration times, while the physical and mechanical characteristics of the potentially mobilizable sediment can be considered fairly uniform. These observations suggest that the rheological properties of the debris flows depend substantially only on the amount of water that impulsively arrives in the sediments of the source area. Due to the lack of homogeneity in space and time of rainfall intensity and distribution, the correct evaluation of the precipitation that really fall in the catchment by means of a rain gauge is necessary. The opportunity to install a wider network of meteorological stations, together with the monitoring of sites affected by debris-flows, will enable a more and more detailed definition of the triggering conditions of these phenomena.

Finally, it should be emphasized the constant increase of channels progressive elongation detected in the period 1954-2015 that could be due to: i) a higher frequency of debris flow phenomena, such as a consequence of a higher frequency of precipitation of maximum intensity, especially those of less than 15 minutes; ii) greater volumes mobilized, as a consequence of the presence of a greater quantity of debris, available after long periods of low rainfall.

In any case, the sharp increase in the rate of elongation of the channels is easily interpretable only in relation to general climatic conditions, as the local variation shows only a slight increase of rainfall in recent decades. In conclusion, the research highlights the extreme complexity of debris flow phenomena and the necessity to understand mechanisms and factors controlling the likelihood of debris flows, as they represent the fundamental basis for both hazard evaluation and proper planning of structural and non-structural measures.

References

APAT Note Illustrative della Carta geologica d'Italia alla scala 1:50.000. Foglio 029 Cortina d'Ampezzo.

Armento M.C. (2007) Le colate detritiche della Conca Ampezzana: Meccanismi di innesco e valutazione della pericolosità. Earth Sciences Ph.D., University of Padova. Supervisor: Prof. R. Genevois.

Armento M.C., Genevois R., Tecca P.R. (2008). Comparison of numerical models of two debris flows in the Cortina d' Ampezzo area, Dolomites, Italy. Landslides 5:143–150. DOI 10.1007/s10346-007-0111-2.

ARPAV (2020). Regional Department of Territorial Security. Meteorological Service – Teolo (Padova).

Berti M., Genevois R., LaHusen R., Tecca P.R. (2000). Debris flow monitoring in the Acquabona watershed on the Dolomites (Italian alps). Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere. Volume 25, Issue 9, pp 707-715.

Berti M., Simoni A. (2005) Experimental evidences and numerical modelling of debris flow initiated by channel runoff. Landslides 2(3):171-182. DOI: 10.1007/s10346-005-0062-4.

California Culvert Practice, 2nd Edition, Department of Public Works, Division of Highways, Sacramento, 1955.

Coussot P., Laigle D., Arattano M., Deganutti A., Marchi L. (1998). Direct determination of rheological characteristics of debris flow, *Journal of Hydraulic Engineering*, 124, n.8, 1998.

Farhan Y. (2017). Applied morphometry and watershed management using RS, GIS ad multivariate statistics (Case Studies). Scientific Researcj Publishing Inc. pp. 484 ISBN: 978-1-61896-410-6.

Genevois R. and Tecca P.R. (2016) - Estimation of the Debris Flow Risk in the Cortina d'Ampezzo area (North-Eastern Italy). In: Proc. 6th Int. Sc. and Tec. Conf. "Modern Problems of Water Management, Environmental Protection, Architecture and Construction", 22-25 September, Tibilisi, Georgia, 212-221.

Genevois R., Tecca P.R., Deganutti A.M. (2018). Debris flow mitigation and control in the Dolomites (Nort-Eastern Italy). *Italian Journal of Engineering Geology and Environment, 2, 57-65. DOI: 10.4408/IJEGE.2018-02.O-04*

Iverson R.M. (1997) The physics of debris flows. Review of Geophysics, 35, 3. Pp. 245-296. https://doi.org/10.1029/97RG00426.

Major, J.J., and Pierson, T.C., 1990, Rheological analysis of fine-grained natural debris-flow material, in Proceedings of the International Symposium on Hydraulics/Hydrology of Arid Lands, July 30-Aug. 2, 1990, San Diego, CA: American Soc. of Civil Engineers, New York, p.225-231.

Major J.J., Iverson R.M. (1999). Debris-flow deposition: Effects of pore-fluid pressure and friction concentrated at flow margins. *GSA Bulletin*, 111, 10; pp. 1424–1434. doi: https://doi.org/10.1130/0016-7606.

Major, J.J., Pierson T.C. (1992). Debris flow rheology: Experimental analysis of fine-grained slurries, Water Resour. Res., 28, 3, 841-857. https://doi.org/10.1029/91WR02834.

Martino R. (2003). Experimental analysis on the rheological properties of a debris-flow deposit. In Debris Flow Mechanics and Mitigation Conference, Davos, Vol. 1. ISBN: 978-9077017784

Marchi L., D'Agostino V. (2004). Estimation of debris-flow magnitude in the Eastern Italian Alps. Earth Surface Processe and Landforms, 29, 2, pp. 207-220. https://doi.org/10.1002/esp.1027.

Martino R. (2003). Experimental analysis on the rheological properties of a debris-flow deposit. In Debris Flow Mechanics and Mitigation Conference, Davos, Vol. 1. ISBN: 978-9077017784

Pierson T.C., Costa J.E. (1987) A rheologic classification of subaerial sediment-water flows. *Geological Society of America Reviews in Engineering Geology*, 7, 1–12.

Phillips C.J., Davies T.R.H. (1991). Determining rheological parameters of debris flow material, Geomorphology, 4, , 101-110.

Roussel M.C., Thompson D.B., Fang X., Cleveland T.G., Garcia C.A. 2005. Time-Parameter Estimation For Applicable Texas Watersheds. Research Report 0–4696–2. Lamar University. SHA 2005. Application of Hydrologic Methods in Maryland. U.S. State Highway Administration.

Tecca P.R., Galgaro A., Genevois R., Deganutti A.M. (2003) Development of a remotely controlled debris flow monitoring system in the Dolomites (Acquabona, Italy). Hydrol Processes 17:1771–1784.

Wang ZY, Lee JHW, Melching CS (2014) River dynamics and integrated river management. Springer Verlag/Tsinghua Press, Berlin/Beijing, p. 226–230.