4

Debris Flow Phenomena: A Short Overview?

Chiara Calligaris and Luca Zini
University of Trieste, Geosciences Department
Italy

1. Introduction

Debris flows are one of the most dangerous and destructive processes affecting the second order streams in the mountain areas (Cavalli et al., 2005; Boniello et al., 2010; Santi P.M., 2008). This very common phenomenon in the Alpine environment is a type of landslide defined by several authors (Varnes, 1978; Hutchinson, 1988; Pierson, 2005; Pierson and Costa, 1987; Coussot and Meunier, 1996; Hungr et al., 2001) trough focusing on the involved material, on the water saturation and on the mass velocity. Debris flows usually consist of a complex mixture of fine (clay, silt and sand) and coarse (gravel, cobbles and boulders) materials with a variable water quantity (Nettleton et al., 2005). The outcoming mixture has a behaviour similar to a viscous "slurry" with a high density, 60% to 80% by weight solids (Varnes, 1978; Hutchinson, 1988; Pierson, 2005). The same Hutchinson (1988) is describing them as "wet concrete".

These phenomena are rapid mass movements, gravity induced able to transport large quantities of sediments and wood downslope, producing complex distribution of deposits and eroding surfaces along their flowpath (Remaitre et al., 2003).

Several other classifications try to define these processes. For example, Aulitzky in 1982 provided a classification focused on the typologies of the materials involved making a macroscopic distinction between the rocks and the engineering soils.

Pierson and Costa, in 1987, proposed their classification basing it on the sediment concentration and on the average flow velocity.

Paoluzzi, Coussot and Meunier, in 1996, described debris flow as a function of sediment concentration and material typology, between hyperconcentrated flows and landslides. Celerity, deposit nature and flow type are the parameters considered. Two of them are appropriate for a practical classification: solid fraction and material type (Paoluzzi et al., 1996).

Hungr in 2001 (Hungr et al., 2001) elaborated a classification having as main distinctive parameters the water content, the velocity and the material typology.

Seen that existing classifications for landslides were based on process, morphology, geometry, movement type and rate, type of material and activity, in 2005, Jakob (Jakob, 2005) proposed a different categorization based on a size classification. This classification is rarely used because it provides too little information on morphology or process characteristics of a landslide. It has been prevailing studied for regional studies along infrastructures corridors because it addresses variables that are part of a hazard evaluation.

Anyway, in the present work, a simple criterion of identification is proposed. Debris flows must be seen as intermediate phenomena between hyper concentrated flows (intense bed load transport) and landslides separated from them by sharp transitions of some characteristics (celerity, deposit nature and flow type). Two parameters, solid fraction and material type, thought to be appropriate for a sound and practical classification, are brought out, and the corresponding complete classification of flow and mass movements in mountain areas is presented. Two extreme debris flow types are thus distinguished: muddy debris flows and granular debris flows.

Regardless of classification, all are agreed that debris flow phenomena, throughout the world, cause considerable damages, but nowadays researchers are trying to better understand their behaviour in order to prevent them, to identify the warning signs and to build alert systems that allow to save many lives and properties. Even if they remain poorly understood, a basic knowledge is available concerning their recognition and propagation.

The knowledge of the possible inundation areas, the thickness of the deposits and the velocity expressed during the event are really useful to define, but especially to delineate the vulnerable areas in order to identify the structural and non-structural mitigation measures that have to be realized to protect the existing infrastructures (Boniello et al, 2010).

The volume and the composition of the mixture of a debris flow are the main factors that contribute to determine the hazards associated with such phenomena, since they govern the mobility and impact energy of the debris (Iverson, 1997; Jakob, 2005). In this regard, an adequate work must be carried out in the field of non-Newtonian fluid mechanics. In particular, one fundamental rheological property of debris flow materials is the yield stress, which explains thick deposits on steep slopes and can be inferred from field measurements. Furthermore it can be used to estimate viscous dissipation within the bulk during the flow. Relevant models predicting muddy/debris flow dynamics are already available whereas further progress is needed concerning granular flows. During the last years, several simulation models and approaches have been implemented (Cesco Bolla, 2008; O'Brien, 1998; Pirulli, 2005; Avolio et al.., 2011; Rickenmann, 1999) and created to reconstruct the path of a debris-flow phenomena, but a believable scenario can be obtained only by resorting to real parameters that are suitable to characterise the involved material (Sosio et al., 2006). Thus, it is necessary to calibrate those available computational codes through back-analysis simulations and laboratory analysis (Tecca et al., 2006).

In this chapter a fast overview will take the reader into the debris-flow world giving some fixed points on these particular events, how they trigger, which are the boundary conditions, how they develop along a slope. Than, an Italian severe damaged area will be described and used as test site for presenting the obtained results that could contribute to the knowledge of these dangerous phenomena.

2. How the debris flows occur? Predisposing and triggering factors

On steep slopes, in mountainous areas, could occur assorted types of flow or mass movement involving water and sediments. Among these events, debris flows are peculiar phenomena during which a large volume of a highly concentrated viscous water-debris mixture flows through a stream channel or on an open plain. For the occurrence of these types of landslide predisposing and triggering factors need to be present in the rough area.

Debris flows are geomorphological easy to recognize on the field. Mainly they are formed by a source area, a stream transport channel and a depositional area having a fan morphology (Figure 1).

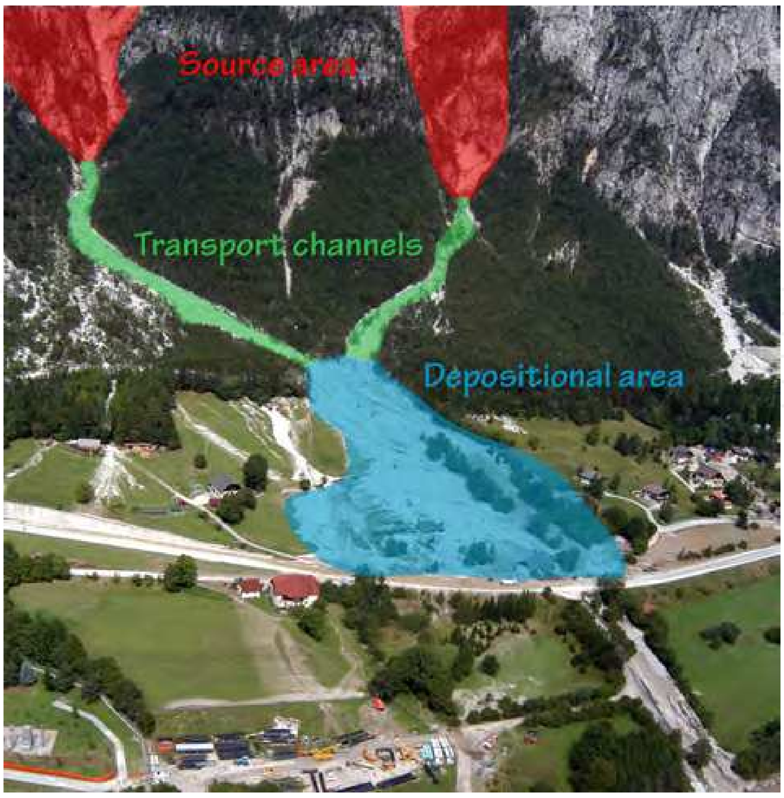


Fig. 1. Identification of the three main parts of a debris flow phenomena: 1) source area, in red; 2) transport channel, in green; 3) depositional area, in blue.

The source area of a debris flow must have the following conditions to be defined a source area: 1) a very steep slope (>15°); 2) an abundant supply of loose debris (Bovis and Jakob, 1999); 3) a source of abundant moisture; 4) spare vegetation.

Among all the predisposing factors, the morphometric parameters play a very important role. They define the geometry of the catchments and their characteristics. Among all the possible parameters, the most important are: the area and the perimeter of the catchment, the average lenght, the maximum, minimum and average elevation, the average slope angle, the shape factor (intended as function of lenght and surface F=0.89L/S) the circularity rate and the Melton number (I_M).

But not only them have a huge impact on debris flow. The most important predisposing factor can be considered the debris avaliability (Bovis and Jakob, 1999). Concerning this sentence, the catchments can be divided in two main categories: one that have limited debris avaliability and the other that have an illimitated avaliability. In this case it is easy to understand when a debris flow can occurr along a torrent adding only the precipitations as triggering factor.

In this sense, a typical characteristic of the debris flow is their close connection with high intensity meteorological events. On one hand, it is possible to say that deep landslides are usually associated with structural causes (morphology, shear strength, etc. …) and triggered by long term weather events, able to saturate deep layers. In the case of debris flow, the slope equilibrium conditions are governed by effective stresses reduction, due to pore water pressure having a hydrostatic distribution. For these reasons, debris flows, but also the soil slips, are typically triggered by high intensity meteorological events occurred in a short time period, that can uplift the water table reaching a critical level (Skempton and Lory, 1957) or, conversely, when the rainfall intensity exceeds the infiltration rate creating a saturated layer from the surface (Green and Ampt, 1911; Fredlund et al., 1978). Anyway, in both cases, infiltration phenomena create an additional system of forces increasing the destabilization.

For all these reasons, a study on the triggering factors of a debris flow should start from a multidisciplinary approach founded on hydrological, meteorological and geotechnical basis.

Debris flow can be triggered also from shallow landslides originating on steep slopes, from landslides in topographic swales or hollows, from the entrainment of materials within stream channels, from diffuse erosion, from rock glacier bursts (Mariis, 2006). Landslides that mobilize into debris flows often occur along topographic concavities, which concentrate groundwater flow and contain thicker accumulations of fine materials than surrounding ridges. Concentrated groundwater flow increases the wetness of clay and fine materials in hollows, making it particularly susceptible to destabilizing groundwater pressure increases during and immediately after rainstorms. Debris stops flowing when the internal kinetic energy drops below the level necessary to maintain the fluid to flow, commonly because slope of the channel through which the debris flows flattens or widens.

Debris flows can be triggered by many other different factors. Among the ones previously described, the addition of moisture can be considered the main one: without water, the debris has no possibilities to occur.

Another triggering factor can be considered the erosion of the material along the banks of the streams. This erosion can cut into thick deposits of saturated materials stacked high up the valley walls removing support from the base of the slope triggering a sudden flow of debris.

Talking about the possible triggering factors, wildfires can be considered one of them, not as the main factor, but as a help in creating boundary conditions. Some debris flows occur after wildfires have burned the vegetation from a steep slope or after logging operations have removed vegetation. Land use is one of the most important surroundings that needed to be taken into account when studying a landslide. The loss of support induced by the removed water from soil and the burning of the roots create the condition for a debris flow to occur: in this case, also a moderate amount of rain on a burn scar can trigger a large event.

Volcanic eruptions and earthquake have also to be considered as triggering factors in debris flow occurring.

Going back to rainfall heavy conditions, the scientific community is trying to define hydrological models on statistic base finalized to identify the critical amount of rain and the tresholds over which the triggering risk can be considered very high.

These tresholds are given by the following empirical equation:

$$I = a\,D^{-b} \tag{1}$$

where I is the rainfall intensity (mm/h) and D is the duration of a rainfall (hours). a and b are empirical coefficients (Bruschi, 2008). For the Friuli Venezia Giulia Region, the only values of a and b have been obtained by Paronuzzi et al.(1998) but they not take into account the recent alluvial events.

Once defined when and under which kind of rainfall conditions a phenomena can be triggered, it is important to quantify the magnitude (M) in order to extimate the flooded areas and to recognize the different hazard conditions.

It is possible to obtain data on magnitude trough empirical methods: among all of these, there are some really simple that correlate magnitude [m^3]with the catchment area S [km^2]

and the average fan slope i, expressed in percentage. Some of the most common methods are the following: Ceriani et al. (2000), Bianco & Franzi (2000), Hampel (1977), D'Agostino et al. (1996) and Marchi & Tecca (1996).

In addition to magnitude, a value that have a real important meanning, is the runoff determination. Its definition permits to identify the extension of the potentially hazardous flooded areas and could be extimated trought the relation proposed by Rickenmann (1999) based on the observation and analysis of 150 swiss catchments. The formula is a product between the magnitude (M) and the difference in elevation between the starting and end point of the triggered debris flow (H)

$$L_{tot} = 1.9\, M^{0.16}\, H^{0.83} \tag{2}$$

All the parameters previously described permit to widely characterize a debris flow, but one thing is still missing. An evaluation on the grain size distribution and the definition of its vertical depositional shape.

Debris flows deposits are characteristically poorly sorted, commonly contain large fragments resting unsupported in a finer-grained matrix, may be internally structureless and may contain elongate fragment strongly aligned approximately parallel to flow surfaces, that are indicative of laminar flow. They ara sometimes characterized by an inverse grading (Fischer, 1971).

Inverse grading can occur in two different type of deposits: distribution inverse grading or coarse-tail grading. The distribution inverse grading shows a steady increase of the grains' dimensions from the base to the top of the deposit and characterizes poor matrix deposits. This kind of flows move through the high rate of grain collisions; in this conditions the coarser clasts are pushed upward by dispersive pressure and/or the finer grains are pushed downward by kinetic sieving (Figure 2).

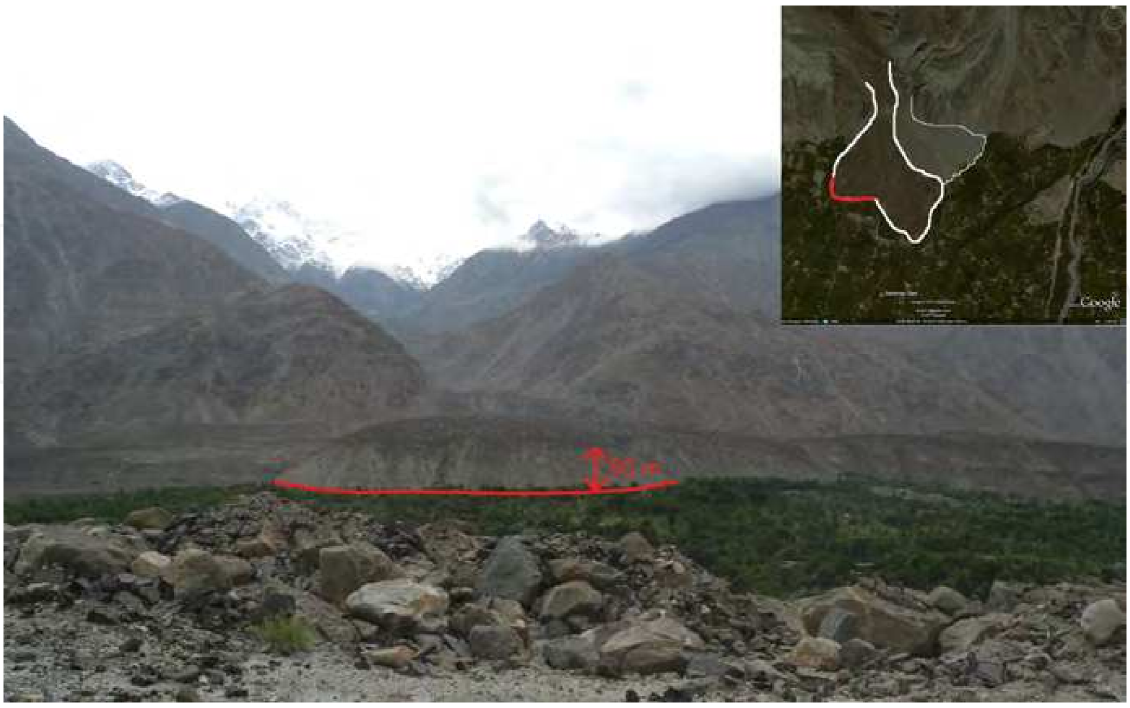


Fig. 2. Debris flow deposit in Gilgit region (north east Pakistan). The inverse gradation is present at the top of the debris.

The coarse-tail inverse grading shows a quite progressive increase of the size of the clasts in the basal layer, while the top contains the largest grains together with a chaotic mixture of sediment. The differential reduction of the matrix strength, caused by shear strain, produces selective setting of coarser clasts from the flow (Postma and Nemec, 1991). In the Friuli Venezia Giulia Region it is very difficult to find a depositional fan with a clear inverse grading. The reason is due to the short flow path and the presence, along the transport and depositional areas of a lot of obstacles as trees, houses or infrastructures. Figure 2 is showing a debris fan in the northern part of Pakistan, close to Gilgit. The dimension of the fan and the flow path permit to the debris mixture to become mature and to make the floating boulders to reach the top of the fan and the frontal area.

3. A case study: More than 300 debris flow in Val Canale valley

3.1 Val Canale, environmental settings

Val Canale valley, located in the extreme north eastern part of Italy, during the last century has been repeatedly affected by debris flow phenomena that generated serious economic and social damages. From a geological point of view, in the valley, outcrop continuously, in the hydrographic right of Fella River dolostones belonging to Sciliar and in the left, scists belonging to Werfen Formation. Fella River entered along one of the major regional thrust fault: the Fella-Sava line (Figure 3).

Val Canale valley, in 2003, during the occurred alluvial event has been severely affected by debris flow phenomena: the quite narrow valley, the steepness of the slopes and the high tectonic grade, created the conditions not only for the predisposing factors, but also for the triggering ones that permitted the developing of geostatic phenomena.

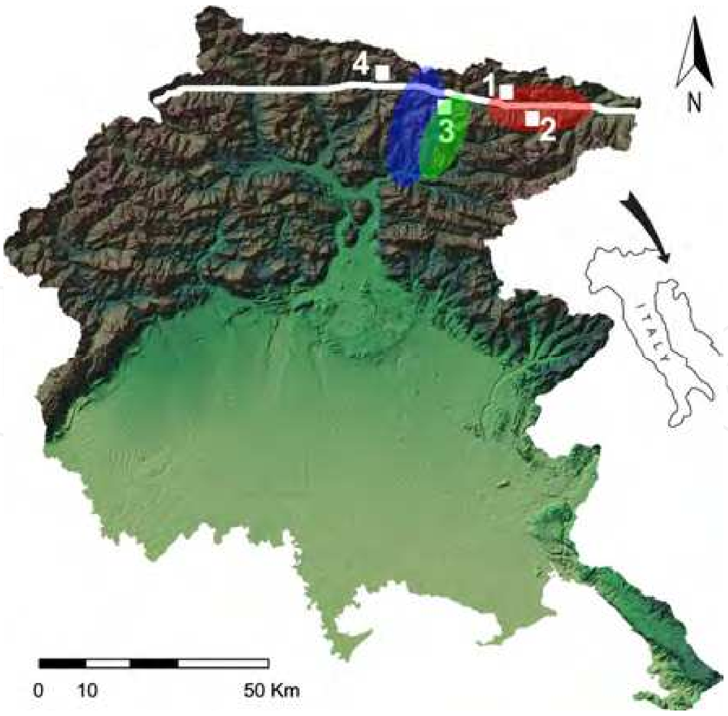


Fig. 3. Friuli Venezia Giulia Region: 1) Malborghetto-Valbruna, Ugovizza and Mount Cucco; 2) Mount Lussari; 3) Pontebba; 4) Paularo. In red: Val Canale valley; in green: Canal del Ferro valley; in blue: Val Aupa valley and Moggio Udinese municipality.

This very intense event, has meant that not only old rock falls or debris were reactivated, but occurred also new hyper concentrated flows that suddenly got into debris flow with a load of debris, mud, boulders and pieces of wood. Tropeano and Turconi (2004) estimated in about 1 million of cubic meters the total amount of debris and sediments mobilized and stored during the event.

The fluvial impact of 29th August produced important modifies on the morphology of the invested area causing severe damages and erosions, creating gullies and expanding the existing riverbeds (Borga et al., 2007). Debris flow invested houses and roads isolating, for days, the villages of Ugovizza, Valbruna, Malborghetto and Pontebba.

For the Val Canale valley, in 2003, was in process of adoption the Hydrogeological Basin Plan (P.A.I. Piano di Assetto Idrogeologico di Bacino) in which were defined areas at risk of debris flow. Its safeguards lines were suspended for the areas affected by the alluvial event of the 29th August due to the commissioner who established it under the occurring of such events. The phenomena occurred during the alluvial event, in some cases, exceeded the perimeters proposed in the Plan. The geostatic phenomena stored thousands of cubic meters also outside the known areas causing severe damages.

In the following years, Civil Defence of Friuli Venezia Giulia Region realized several mitigation measures in the hit areas, for this reason, was discerned the need to upgrade the perimeter areas using tools able to ensure their non-subjectivity. In this respect, are increasing the prospects of software development capable to provide modelling scenarios more and more responsive to realty.

As test sites for the whole area researchers of Geosciences Department studied 12 catchments that have been affected by debris flow phenomena. On every single basin has been realized a back analysis simulation trough commercial software called FLO-2D (O'Brien et al., 1993) this permitted to define physical and rheological parameters that better reproduce the occurred phenomena. For some of the basins different approaches have been used in order to define the runoff and the expansion areas: DF-SIM (for Rio Cucco basin) and Debris software (for Pontebba 01 basin) have been used (Di Gregorio et al., 1994; Segre at al., 1995; Bruschi, 2008).

For Fella sx catchment a rheological specific study has been realized. This permitted to go deeper into the rheology world and to try to better define characteristic values of viscosity and yield stress that heavy influence these so complex phenomena.

3.2 The alluvial event

The north eastern part of Friuli Venezia Giulia Region, especially Val Canale valley, Canal del Ferro and Aupa valleys have been interested, on 29th August 2003, by harsh weather conditions characterized by heavy rainfall since 12 o'clock. Rainfalls firstly affected high mountain areas, between Mount Cucco and Malborghetto-Ugovizza pastures, and then moved downstream with a gradually increasing intensity.

Pontebba's rain gauge, which is part of the network managed by Regional Directorate of Civil Defence, was the only instrument, close to the study area, that worked properly during the alluvial event. Data recorded by Pontebba's rain gauge, indicate the extreme gravity of the occurred phenomenon. Since 1928, when rainfall data recording started, had never occurred events of this entity. In the range between 1928 and 2010, the only comparable event was on 22nd June 1996 when occurred 78.4, 155, 345.6 and 465 mm of rain in 1, 3, 6, 12 and 24 hours respectively (Table 1).

Time (hours)	Height (mm)	
	Pontebba (1996)	Pontebba (2003)
1	78.4	88.6
3	155.0	233.4
6	199.6	343.0
12	345.6	389.6
24	465.0	396.2

Table 1. Heigh and duration time of rainfalls recorded by Pontebba's rain gauge (modified from Norbiato et al., 2007).

What is clear from data recorded on 2003, is that the event has reached remarkable precipitation values especially in the ranges between 3 and 12 hours. Specifically: have been observed maximum values of 50.8 mm in 30 minutes (between 17 and 17.30), of 88.6 mm for an hour (15.30 – 16.30), of 233.4 mm for three hours (14.30 – 17.30) and of 343.0 for six hours (12.0 – 18.0). The total amount of the event, which lasted about 12 hours, was equal to 389.6 mm. If compared with the series of heavy rainfall recorded by Pontebba's rain gauge and processed using Gumbel distribution, precipitations of 29th August 2003 are associated to a return time of over 100 years. Particularly impressive are the values corresponding to 3 and 6 hours. The strong detected intensities are in accordance with the great intensity of the morphodynamics actions induced by this event (Norbiato et al., 2007).

The most part of the landslides has been triggered between 14.00 and 18.00 when, at Pontebba's pluviometric station has been recorded a total rainfall value equal to 293.0 mm. On the northern side of the alignment Pontebba – Ugovizza occurred limited bursts over 400 mm (Borga et al., 2005).

Borga's researchers (2005) realized on signal probabilities rainfall lines, obtained trough linear moments method and GEV model (Generalized Estreme Value) for the north east Italian area, recognized the statistical rarity of the event that generated the 2003 flash flood in Val Canale.

2003 event, with its extraordinary features, is not an isolated one in the climatologic context of the Region: the event magnitude is in fact comparable to the one of other two events occurred in the previous 20 years and happened on 11st September 1983 with the center in Paularo and the second on 22nd June 1996 with the center on Moggio Udinese, Pontebba and Paularo areas.

These observations emphasise that extreme events are really rare if one refers to the specific site, while they occur with not negligible frequency when one considers the entire mountain areas of the Region. In Borga's paper were also estimated the return time of the heights of rain in August 2003 in Pontebba. Return times characterizing the event vary considerably with the duration: for duration between 1 and 24 hours, return time is calculated to be between 50 and 100 years; for 12 hours it is between 200 and 500 years, while for duration between 3 and 6 hours return time has been calculate to be in the range between 500 and 1000 years (Borga et al., 2005; Zanon, 2010).

3.3 Debris flow simulations in the 12 basins

12 catchments tributary of Fella River were chosen to realize debris flow event simulations (Calligaris et al., 2008). Everyone has been analyzed separately, but the methodological approach has been the same for all of them.

Rio Cucco basin has been modelled also with another software called DF-SIM, developed in an original way by O.U.C. Civil Defence and Soil Defence of Udine Province. Torrent Pontebba 01 has been analyzed instead, trough DEBRIS commercial software.

3.3.1 FLO-2D for simulating events in 12 basins

The two-dimensional numerical code FLO-2D is based on volume conservation. This code simulates a debris flow event along a defined topographical surface, using, as input data, an inflow hydrograph, the plastic viscosity of the material and the yield stress, being these a function of the Concentration by volume.

For the basins, the simulation has been realized on a computational domain made by a grid of 5m*5m obtained from the regional cartography CTRN at a scale 1 to 5.000 o, where possible, from laser scanner data.

Inflow hydrographs have been realized by the researchers of Padova University (Dipartimento Territorio e Sistemi Agro Forestali) that developed an hydrologic model spatially distributed (KLEM) setting it on the alluvial event of 29th August. The model uses rainfall data coming from rain gauges stations and from high resolution radar observations (Borga et al., 2007). For the back analysis, seen that rheological data were not available, have been used parameters described in literature and characteristics of the studied lithologies (O'Brien et al., 1988).

For every basin, at least 12 simulations have been realized (Figure 4), varying every time the input data and determining the physical and rheological couples of parameters that better approximate, as flooded area and thickness of deposits, the occurred event (Table 2).

η		τ		References	Studied basin
α_1	$\beta1$	$\alpha2$	$\beta2$		
0.036	22.1	0.181	25.7	Aspen Pit 1	Pontebba 2
0.0538	14.5	2.72	10.4	Aspen Pit 2	Rio Pirgler
0.00136	28.4	0.152	18.7	Aspen Natural Soil	Malborghetto Centro, Abitato Cucco
0.128	12	0.0473	21.1	Aspen Mine Fill	Malborghetto est, Studena bassa
0.000495	27.1	0.0383	19.6	Aspen Watershed	Fella sx
0.000201	33.1	0.291	14.3	Aspen Mine Source Area	Rio Cucco, Rio Ruscis
0.00283	23	0.0345	20.1	Glenwood 1	
0.0648	6.2	0.0765	16.9	Glenwood 2	
0.00632	19.9	0.000707	29.8	Glenwood 3	
0.000602	33.1	0.00172	29.5	Glenwood 4	Malborghetto nuovo, Pontebba 1
0.0075	14.39	2.6	17.48	Dai et al. (1980)	
0.0075	14.39	0.152	18.7	Tecca et al. (2006)	

Table 2. Couple of rheological parameters responding to the different hydrogeological context used for the back analysis simulations (from O'Brien et al., 1985). In the last column has been reported the correspondence with the studied basins.

Concerning Concentration by volume (Cv), values were varying in the range between 0.2 and 0.55. For the Manning coefficient has been used a value of 0.1, typical of soils made of debris deposits with no bushes on them. The specific weight of the mixture γ_m and the resistance parameter for laminar flow K, were assumed to be 26.5KN/m^3 and 2085 respectively, values usually used in literature (Boniello et al., 2010; Calligaris et al., 2009; Tecca et al., 2006).

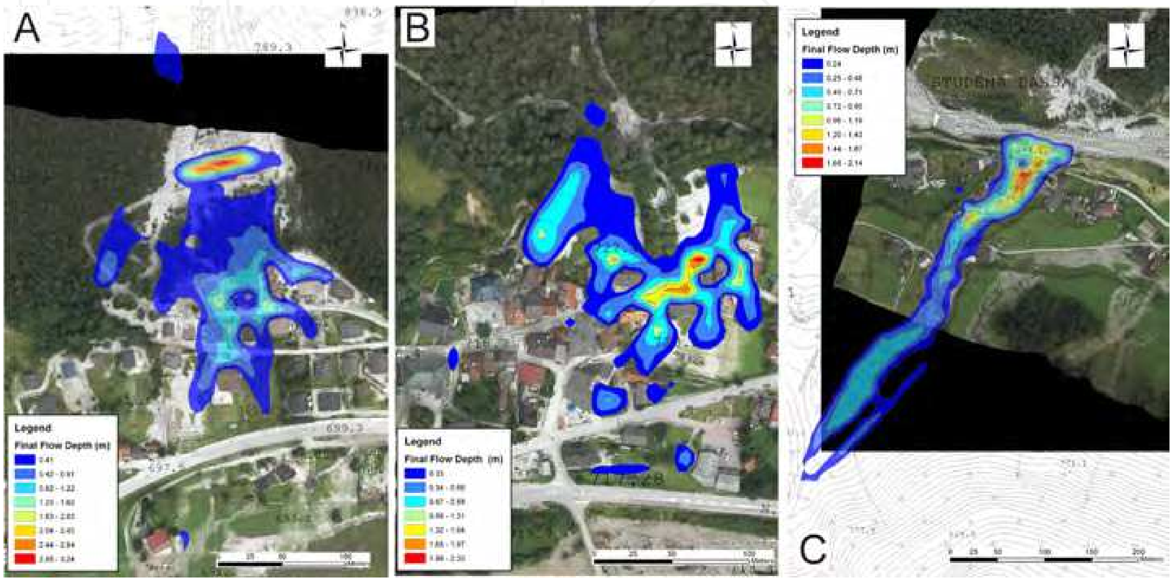


Fig. 4. Three of the twelve analyzed basins, flooded areas and heights of deposit: A) Abitato Cucco basin; B) Malborghetto centro basin; C) Rio Ruscis basin.

3.3.2 Rio Cucco simulation using DF-SIM

The calculation code has originally been developed by U.O.C. Soil Defence and Civil Protection of Udine Province. The program allows reproducing a debris flow phenomena adopting the cellular automata theory (CA) (Segre et al, 1995; Di Gregorio et al, 1994). A model for cellular automata is a complex system represented as simple composed of many parts; each of them, to evolve, has its own internal rule and interacts only with the parties close to it. Each automaton making system can take states and receive input according to a discrete time scale from where it is immersed and react to these challenges with a transition state or a response (output). The system evolution is performed through a transitional function used at each time step. In this way, it is possible to determine the new state of each cell starting from the current status and from cells state making up the neighbourhood of the cell itself.

A pretty flexible tool for debris flow simulation can be obtained through modelling based on Cellular Automata Theory; varying appropriately control parameters, the simulator fits the different rheological and fluid dynamics characteristics. With this software has been possible to simulate the event occurred on Rio Cucco and compare the obtained results with the one obtained from FLO-2D simulation (Figure 5).

Trough DF-SIM is possible to characterize the debris flow behaviour with the following parameters: solidification, dynamic friction angle and internal friction angle (characteristic parameters), critical height and humidity (critical parameters). Not only topographical files but also information about sediment sources areas, their location and debris thickness are

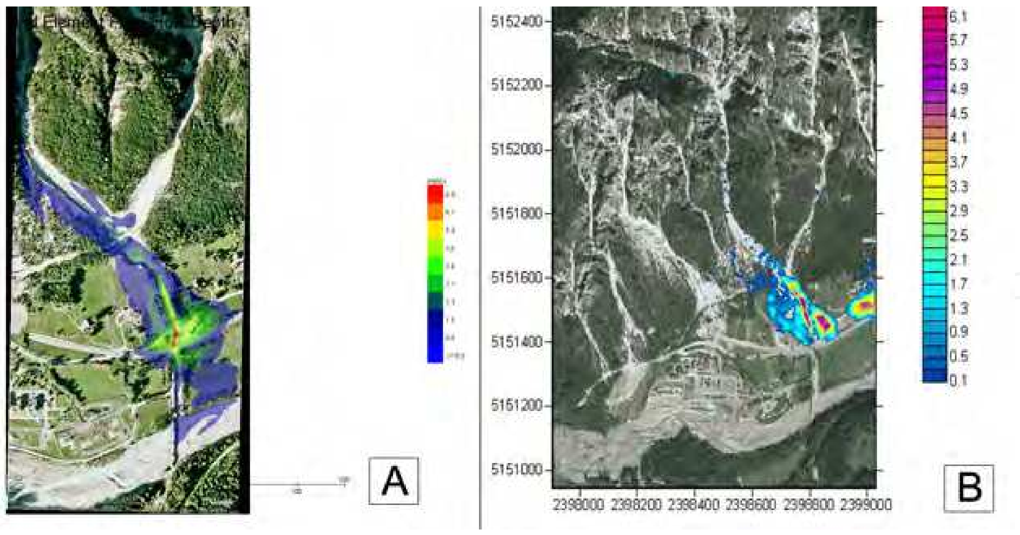


Fig. 5. A) Rio Cucco scenario event realized trough FLO-2D software; B) same scenario realized with DF-SIM software.

requested to run the simulation. For Rio Cucco, a total volume of about 100,000 m^3 was determined on the basis of the debris expansion areas outlined on field just after the event.
Like for the volume, parameter values useful for the simulation were empirically defined. Several back-analysis simulations were performed with different parameters in order to obtain a good matching between flooded areas and thickness of deposits observed post-event and the simulated ones.

3.3.3 Pontebba 01 simulation using DEBRIS

Debris is a software that allows performing evaluations and inspections related to debris flow phenomena, analyzing their two-dimensional motion or evaluating the magnitude in the fan area. The software is organized with a vertical structure that makes obligatory to follow a precise sequence of commands to perform the analysis, in order to successfully insert the all data required. The code is composed by two sections: a one-dimensional one regarding the river auction until the outlet on the fan on which are calculated the discharge, the heights of debris at a decided section starting from a pure water hydrograph and a two-dimensional section regarding only the fan. To obtain good results, this last section needs as input data a detailed topography on which calculating the dynamic mixture on the fan. The two modules do not evaluate the triggering possibilities, but simulate the flow when it is already triggered. Output files are concerning the following variables: heights of flow, heights of stored debris, final topographic elevations, flow velocity and direction and a file regarding the phenomena intensity classes (intensity evaluated as pressure and heights of stored debris).
Made all the computes, it is possible to visualize the results, in a graph showing, for every path segment, the flow velocity and heights, indeed the point in which the debris is starting its deposition and the indicative runoff.
With the kinematic wave theory instead, the same parameters are calculated on the base of Arattano and Sauvage (1992) theories but visualized with the same mode as the ones obtained with the Takahaski theory (1991). A comparison between the obtained results is necessary to evaluate heights and velocity of the front of the debris while evolving the phenomena along the transport area. For the velocity others evaluations are available.

For the present work, a comparison has been realized between the results obtained trough FLO-2D software and Debris one (Figure 6). Results in plan are different due to the different approaches used by the two softwares, but heights of debris and flow velocity are comparable.

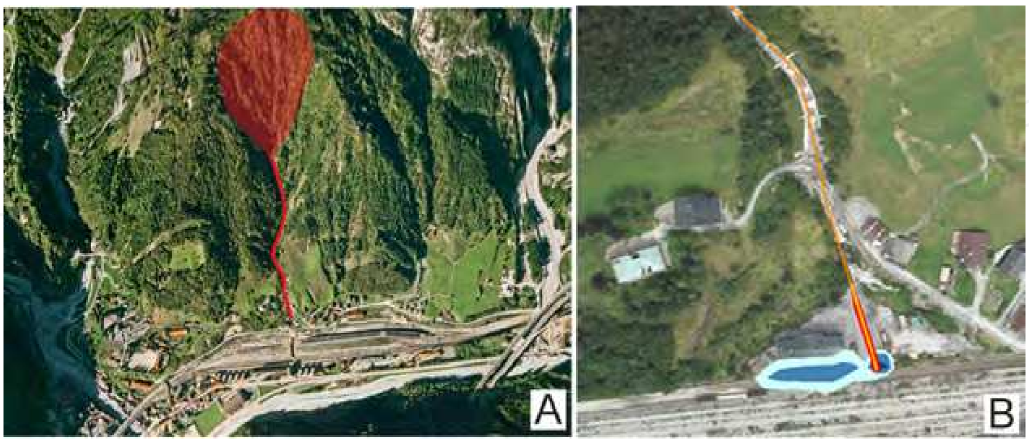


Fig. 6. Pontebba 01 basin: A) Location of the studied area; B) Comparison between obtained results (in the ranges of blue: Flo-2D simulation; in the ranges of red, mapped results with the software Debris).

3.4 Debris flow rheological characterization: an example on Fella sx basin

The debris flows mixture composition and the involved volumes are the main factors that must be defined to determine their hazard: from them, indeed, depend their energy and impact. To find an answer to the question, is fundamental to characterize the material involved in the detritical flow (debris flow or mud flow). According to some authors (Whipple, 1992; Calligaris et al., 2010), it is really difficult to establish a correlation between the rheological parameters identified trough laboratory analysis and the ones obtained trough empirical tests with the help of simulators.

In the examinated area, in Val Canale valley, some tests have been realized to try to better define viscosity and yield stress. An example will be shown on Fella sx basin (Figure 7).

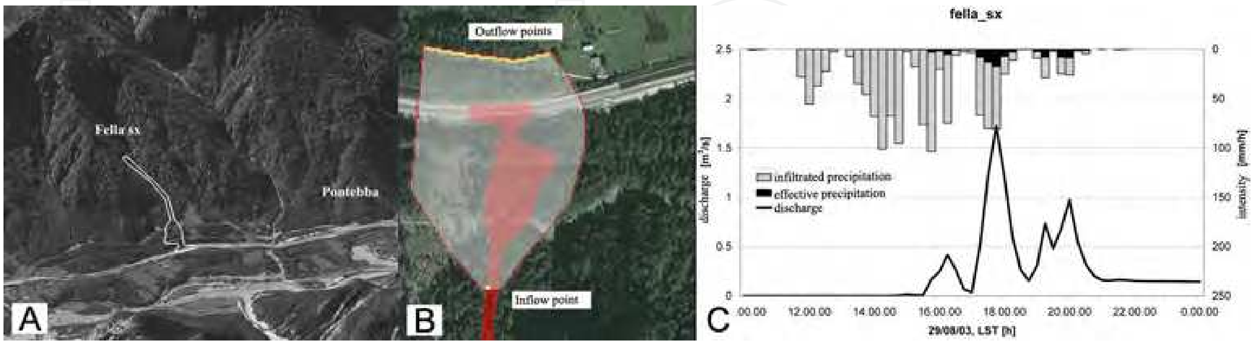


Fig. 7. A) Fella sx location; B) Computational domain; C) Inflow hydrograph.

For the studied sites, the flow can be considered monophasic and viscoplastic, and in a first approximation, governed by the clay that determine its plastic viscosity and the yield stress.

Knowing the variation of these parameters with the solid concentration, is possible to proceed to a numeric simulation of the phenomenon trough the use of computer codes as previously realized in order to compare the obtained values with the ones gained from the best fitting simulation (back analysis). Several limitations are recognizable in this approach due to the too driver schematization for a so complex phenomenon and for so many parameters, but anyway is a new frontier that will permit to the professionals to use and simulate run out with a good approximation being able to predict future scenario events.

Samples collected along the transport area, have been submitted to the grain size analysis, and on the finer fraction than <0.063mm, a rheological analysis has been realized.

Gran size analysis highlighted a 64.8% of gravel, a 14.8% of sand and a 20.4% of silt and clay defining the sample as a gravel with sandy silt. The rheological studies concerned the fine fraction (passing at 63 μm) obtained through the sieving of the collected samples. With this fraction have been prepared suspensions with a different water weight: 33, 36, 40, 44 and 48%.

The tests consisted of a sequence of segments at a constant stress with increasing values in a geometric progression that highlighted that all the examinated systems have a plastic behavior. Figure 8 explains, as example, the system answer at 40%, described in terms of viscosity and deformation.

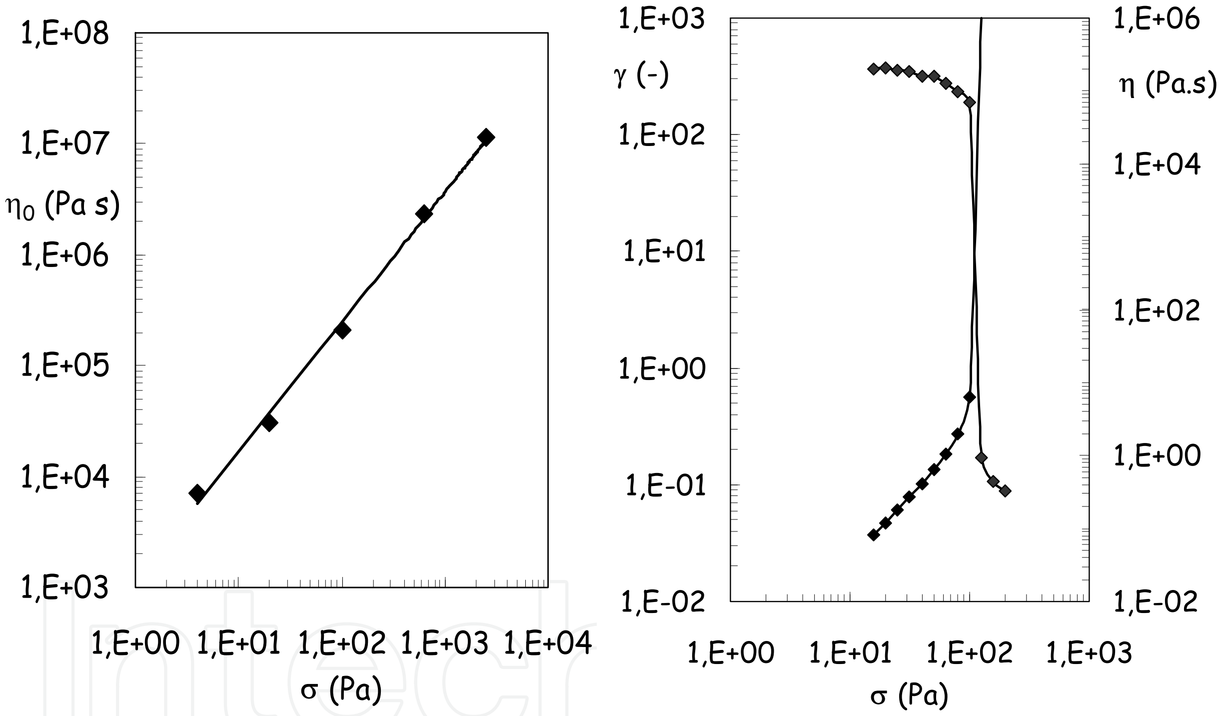


Fig. 8. A) plastic answer to the system at 40% of water content; B) correlation between parameters η_0 and σ_y of the examinated systems.

At low stresses, the answer of the system is viscoelastic: the deformation is firstly linearly increasing with the stress and it is possible to identify a Newtonian plateau of viscosity η_0. Later, in a short interval of stress values, the system goes to a regime of continuous deformation to a significant flow condition and, just after to the sample brake. The apparent yield stress σ_y can be placed in correspondence of the point that define the drop of viscosity, or the sharp increasing of the deformation. For all the systems the transitioning deformation/flow happen in the same range of deformation values (between 0.3 and 0.6), while η_0 and σ_y increase with the concentration of the solid phase (Figure 8B).

To characterize the shear-dependent behavior in the region of medium to high shear rates, is preferable the sequential procedure at controlled rate.
Data obtained can be correlated, with a sufficient approximation, with Bingham model; the correlation is similar to the one obtainable with the other plastic models at three parameters (Casson in the generalized version, Herschel-Bulkley). Table 3 shows Bingham parameter values (η_p,σ_B) and the experimental yield stress σ_y. Even if the values are correlated, their σ_y and σ_B recall the multiplicity of values that can be assigned to the yield stress, since they are dependent from the procedure adopted for their determination.

%		33	36	40	44	48
C_v	(-)	0.421	0.389	0.349	0.313	0.279
σ_B	(Pa)	1254	261	132	25.0	2.03
η_p	(Pa s)	30.5	1.40	0.12	0.10	0.06
σ_y	(Pa)	2500	630	100	20.0	4.0

Table 3. Parameters of Bingham model and experimental yield stress values.

To describe the dependence of η_p and σ_B from the concentration by volume C_v, the most frequently used exponential relations were adopted, although being the same inconsistent when extended at low and high solid content:

$$\eta_p = \alpha \exp(\beta c_v) \quad \sigma_B = \gamma \exp(\delta c_v) \tag{3}$$

3.4.1 FLO-2D computational code to simulate debris flow scenario event

To model the phenomenon on Fella sx has been used the FLO-2D software. The two-dimensional numerical code has been used for the back analysis trough the model of Aspen Watershed defining with the following rheological parameters: $\alpha = 4.95*10^{-5}$, $\beta = 27.1$, $\gamma = 3.8*10^{-2}$ and $\delta = 19.6$ that best approximate the event occurred for inundated area and thickness of the stored deposits.
Subsequently, several numerical simulations were carried out using the parameters obtained from correlation of experimental data and postulating different peak of concentration by volume (0.35, 0.42, 0.50). From the tests at controlled rate were obtain the following values: $\alpha= 2.49*10^{-13}$, $\beta=76.5$, $\gamma=3.44*10^{-3}$, $\delta=29.55$; from the one conducted at controlled stress dedicated to the measurement of the yield stress, the following results were obtained: $\gamma'=1.67*10^{-5}$ and $\delta'=44.75$. During all the simulation phases, the value of Manning coefficient was 0.1, the weight of volume γ_m and the resistance flow parameter K have been estimated at 26.5 kN/m^3 and 2085, respectively (O'Brien et al., 1988; Tecca et al., 2006)

3.4.2 Results and discussion

Simulations of the phenomenon were realized at different values of concentration by volume peak and produced 9 different scenarios, three of which are derived from back analysis (Figure 9, scenario A, B and C), the others come out from the two sets of experimental data ($\alpha - \beta - \gamma - \delta$, $\alpha - \beta - \gamma' - \delta'$). The comparison has given the way to verify that at small values of Cv (0.35 – scenarios A, D, G), the behavior of the debris mixture is very similar in all three cases. With the increase of the value of Cv (up to 0.5), we are witnesses of an increase in the flooded area and of a flow divagation that mainly tends to

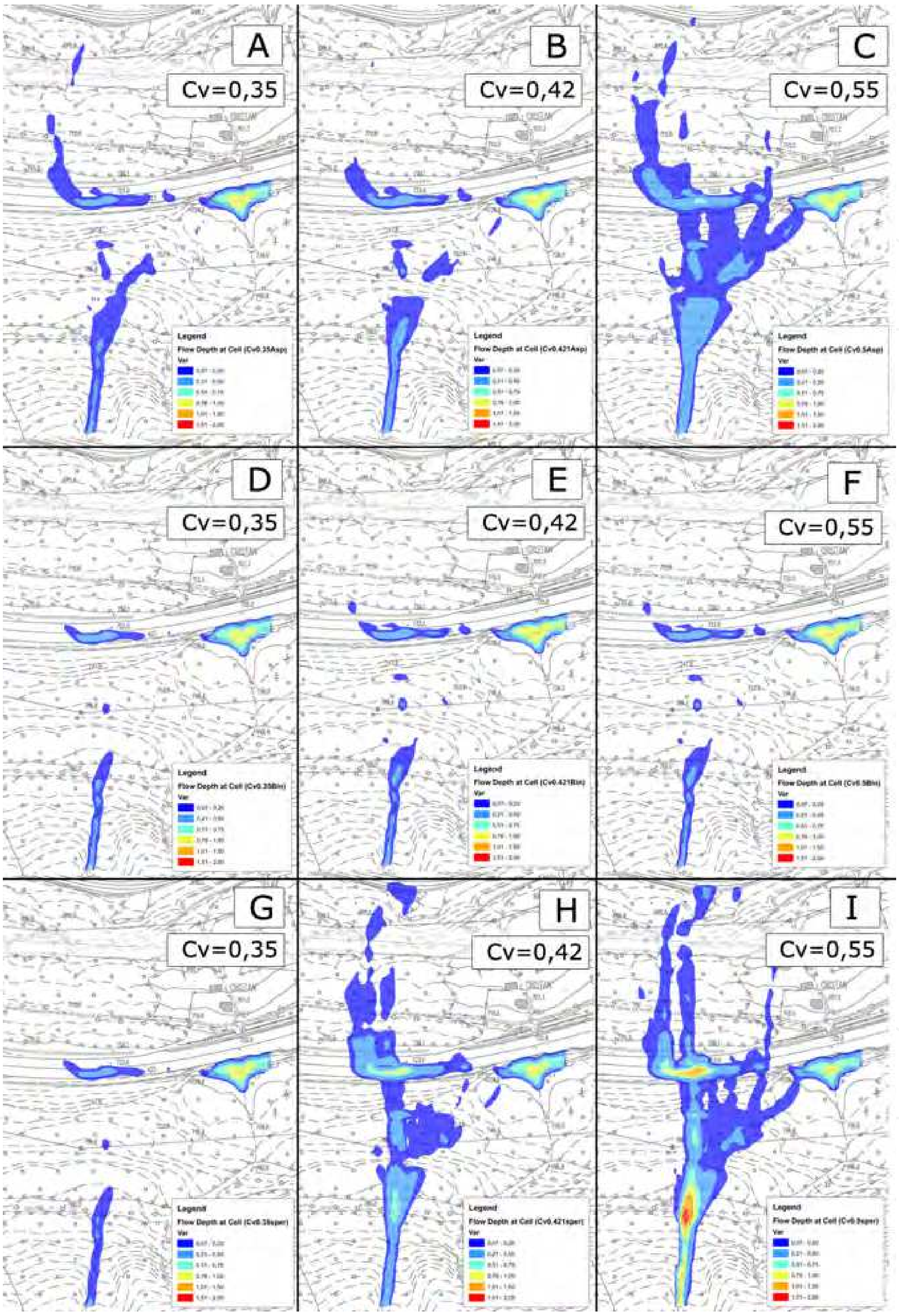


Fig. 9. Simulation scenario proposed (flooded area and thickness of the deposits). A, B, C: Aspen Watershed parameters; D, E, F: parameters obtained from Bingham α–β–γ–δ; G, H, I: parameters obtained from experimental data α–β–γ'–δ' for different values of C_v: 0.35 (A, D, G); 0.42 (B, E, H) and 0.50 (C, F, I).

the right side. At the Cv variation, the plastic viscosity and the yield stress vary considerably and with them also the scenarios produced by the numerical simulation. Nevertheless, they outline similar debris flow divagations of the mixture. The scenarios C and I proposed in Figure 9, point out that the rheological parameters obtained experimentally $\alpha - \beta - \gamma' - \delta'$, although differing from a numerical point of view from those extrapolated from back analysis, allow a good representation of the analyzed event whether the method of deposition are different: in scenario I we are witnessing in a debris accumulation at the transport channel which is not happening during the simulation of scenario C. Scenario I is more similar to the event occurred than the C one.

3.5 Areas at risk ridefinition

The procedure for hazard assessment has been realized using the reference of the Adriatic Basin Authority within the norms for the preparation of the Basin Plan (ADB, 2007). They include the evaluation of the hydrogeological risk by dividing the outlined areas into 4 hazard classes from P1 to P4, from moderate to very high hazard.

The methodological protocol proposed by the Basin Authority takes up the Swiss method (Bundesamt für Umwelt, Wald und Landschaft - BUWAL, 1997) and context it to its territorial jurisdiction (ADB, 2007).

The procedure provides that any landslide has to be characterized in according to three parameters: the geometric severity, speed and return time. Each parameter is divided into three classes.

These parameters have to be inserted in matrices at cascade defining the magnitude and hazard for every single phenomenon.

In all those situations where data on the geometric severity are not available and it is not possible to make an estimation of the damages, the hazard can be defined directly intersecting the velocity data with the frequency.

In the case of debris flows, the application of this method is simple for all those cases where informations about events that have already happened are available but it becomes very uncertain and subjective in all those situations in which there is no data, or in those basins where are present mitigation measures. Here the use of simulators can assist and provide more objective data as base for the application of the method and the definition of the areas at risk.

Here are the criteria by which areas at hydrogeological risk have been redefined in Val Canale valley.

The outline of the flooded areas and store heights of debris in the 12 analyzed basins were made, when possible, by entering directly into the matrix of the BUWAL Protocol, with the values recorded immediately after the event of 2003 (the last event occurred in the investigated area characterized by return time of 500-1000 years).

In all the basins in which no post-event surveys were carried out, the flooded areas and heights of deposit were derived by integrating the data with the ones obtained from the simulations.

In the basins in which have been realized, after the flood of 2003, mitigation measures, the flooded areas and heights of deposit have been refined by integrating the available data with the results of simulations that took into account the works done. Downstream of the mitigation works in which the simulations where no highlighting leakage of material, a review of hazard levels has been realized by decreasing the value of it of at least one class such as in the case of Malborghetto basin center (Figure 10).

Fig. 10. Area at risk for Rio Malborghetto centro basin: A) Outlined area just after the 2003 alluvial event, B) Simulated event, C) New perimeter.

4. Conclusion remarks and outlooks

The present contribute wanted to be an overview on the debris flow world, describing generally the predisposing and the triggering factors, its magnitude, morphometric and rheological parameters and some of the software that nowadays permit to contribute to the reconstruction of a scenario event. This because debris flows are still one of the most dangerous phenomena due to their velocity and quickly happening. At the present time researchers are trying to go deep into the different parameters that characterize a so complex phenomenon in order to try to better define it and to be able, in the future, to simulate a real phenomena. So, the future goal will be to define clearly the input variables in order to better understand the construction of debris flow fans and to predict, mitigate or control the hazard posed by these phenomena to communities situated into mountain areas. For this reason, rheological analysis and debris flow hydrograph will be the two most studied variables in the next years.

5. Acknowledgment

The present work was supported by the Geosciences Department of Trieste University and the Geological Survey of Friuli Venezia Giulia Region. The authors would like to acknowledge prof. F. Cucchi for his valuable comments and suggestions during the study and for the patience; furthermore dott. Chiara Boccali for helping with the images.

6. References

Arattano, M., Sauvage, W. (1992) A kinematic wave model for debris flow, *U.S. Geological Survey Open File Report*, pp.92-290

Aulitzky, H. (1982). Preliminary two-fold classification of torrents. *Mitteil. der Forst. Bundesversuchsanstalt*, Vol.144, pp. 243-256

Autorità di bacino dei fiumi dell'Alto Adriatico (2007). *Progetto di piano stralcio per l'assetto idrogeologico dei bacini dei fiumi Isonzo, Tagliamento, Piave, Brenta-Bacchiglione*, Variante 1, adottato con delibera del comitato istituzionale No.4, June 19, 2007

Avolio, M.V.; Bozzano F.; D'Ambrosio, D.; Di Gregorio, S.; Lupiano, V.; Mazzanti, P.; Rongo, R. & Spataro, W. (2011). Debris flow simulation by cellular automata: a short review of the SCIDDICA models. *Italian Journal of Engineering Geology and Environmental*, DOI 10.4408/IJEGE.2011-03.B-044, pp. 387-397

Bianco, G., Franzi, L. (2000). Estimation of debris flow volumesfrom storm events. *Debris Flow Hazard Mitigation: Mechanics, Prediction and Assesment*. Wieczorek & Naeser (eds), Balkema, Rotterdam, pp.441-448

Borga, M.; Vezzani, C. & Dalla Fontana, G. (2005). Regional rainfall depth-duration-frequency equations for an alpine region. *Natural Hazards*, Vol.36, pp. 221-235

Borga, M.; Boscolo, P.; Zanon, F. & Sangati, M. (2007). Hydrometeorological analysis of the 29 August 2003 flash flood in the eastern Italian Alps. *Journal of hydrometeorology*, Vol.8, pp. 1049-1067

Boniello, M.A.; Calligaris, C.; Lapasin, R. & Zini, L. (2010). Rheological investigation and simulation of a debris-flow event in the Fella watershed. *Nat. Hazards Earth Syst. Sci.*, Vol.10, pp. 989-997

Bovis, M.J. & Jakob, M. (1999). The role of debris supply conditions in predicting debris flow activity. *Earth surface and landforms and processes*, Vol.24, pp. 1039-1504

Bruschi, A. (2008). *Colate detritiche – Stima del percorso e della pericolosità,* Dario Flaccovio Editore, ISBN 978-88-7758-801-2, Palermo, Italy, 183 pp.

BUWAL (Bundesamt für Umwelt, Wald und Landschaft); BWW (Bundesamt für Wasserwirtschaft) & BRP (Bundesamt für Raumplanung) (1997). *Berücksichtigung von Massenbewegungsgefahren bei raumwirksamen Tätigkeiten*, Bern, Switzerland, 42 pp.

Calligaris, C.; Boniello, M.A. & Zini, L. (2008). Debris flow modelling in Julian Alps using FLO-2D, In: *Monitoring, simulation, prevention and remediation of dense and debris flows II*, D. De Wrachien, C.A. Brebbia & M.A. Lenzi, (Eds.), 81-88, Witpress, ISBN 978-1-84564-118-4, Southampton, UK

Calligaris, C.; Boniello, M.A.; Kranitz, F.; Manca, P. & Zini, L. (2009). Areas subjected to debris flow phenomena in Friuli Venezia Giulia Alps, *Proceedings of 6th Euregeo*, Vol.1, pp. 37-40, Mϋnich, Germany, June 9-12, 2009

Calligaris, C.; Cucchi, F.; Nicola, G.; Zini, L.; Kranitz, F. & Manca, P. (2009). Modellazione della colata detritica del Rio Ruscis (Val Pontebbana). *Rassegna tecnica del Friuli Venezia Giulia*, Vol.4, pp. 25-29

Calligaris, C., Lapasin, R.and Zini, L. (2010). Caratterizzazione reologica e modellazione di colate detritiche nel bacino idrografico del Fella. *In proceedings of XI CONVEGNO NAZIONALE DI REOLOGIA*, pp.165-170

Calligaris C., Zini L., Kranitz F. and Manca P. (2011) Delimitazione delle aree a rischio da collate detritiche in Friuli Venezia Giulia. In proceedings of: dissesto idrogeologico-il pericolo geoidrologico e la gestione del territorio in Italia; Roma 10 giugno 2011. In press.

Cavalli, M. & Grisotto, S. (2005). GIS-based identification of debris flow dominated channels: application to the upper Avisio Basin (Trento). Servizio Sistemazione Montana della Provincia Autonoma di Trento, Interreg III Project Alpine Space, Work Package 7, Innovative Tools for Information Collection

Cerini. M., Crosta, G., Frattini, P. & Quattrini, S. (2000). Evaluation of hydrogeological hazard on alluvial fans. *Proc. Int. Symp. Interpraevent 2000*, Villach - Austria

Cesco Bolla, B. (2008). *Modellazione di colate detritiche: software a confronto*. M.S. Thesis, Geosciences Department, University of Trieste, Italy, 91 pp.

Coussot, P. & Meunier, M. (1996). Recognition, classification and mechanical description of debris flows. *Earth-Science Reviews*, Vol.40, No.3-4, pp. 209-227.

D'Agostino, V., Cerato, M. & Coali, R. (1996). Il trasporto solido di eventi estremi nei Torrenti del Trentino Orientale. *Int. Symp. Interprevent.* , Vol. 1, pp. 377-386

Di Gregorio, S.; Nicoletta, F.; Rongo, R.; Spezzano, G.; Talia, D. & Sorriso-Valvo, M. (1994). Landslide simulation by cellular automata in a parallel environment, *Proceedings of 2nd International Workshop on Massive Parallelism*, pp. 392-407, Capri, Italy, October 3-7, 1994

Fisher, R.V. (1971). Features of coarse-grained, high-concentration fluids and their deposits. *Journal of sedimentary petrology*, Vol.41, No.4, pp. 916-927

Fredlund, D.G.; Morgenstern, N.R. & Widger, R.A. (1978). Shear strength of unsaturated soils. *Canadian Geotechnical Journal*, Vol.15, No.13, pp. 313-321

Green, W.H. & Ampt, G.A. (1911). Studies on Soil Physics: 1. Flow of Air and Water Through Soils. *J. Agric. Sci*, Vol.4, pp. 1-24

Hampel, R. (1977). Geschiebewirtschaft in Widbachen. *Wildbach und Lawinenverbau*, Vol.41, pp.3-34

Hungr, O.; Evans, S.G.; Bovis, M.J. & Hutchinson, J.N. (2001). A review of the classification of landslides in the flow type. *Environmental and Engineering Geoscience*, Vol.VII, No.3, pp. 221-228

Jakob, M. (2005). A size classification for debris flows. *Engineering Geology*, Vol.79, pp. 151-161

Marchi, L. & Tecca, P.R. (1996). Magnitudo delle colate detritiche nelle Alpi Orientali italiane. *Geoingegneria Ambientale e Mineraria*, Vol. 33(2/3), pp.79-86

Mariis (2006). Debris flow, Available from: http://www.unicaen.fr/mountainrisks/

Nemec, W. & Postma, G. (1991) Inverse grading in gravel beds. *In: Abstracts IAS 12th Regional Meeting, International Association of Sedimentologists*, p. 38

Norbiato, D.; Borga, M.; Sangati, M. & Zanon, F. (2007). Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. *Journal of Hydrology*, Vol.345, pp. 149-166

O'Brien, J. & Julien, P.Y. (1985). Physical process of hyperconcentrated sediment flows, *Proceedings of the ASCE specialty conference on the delineation of landslides, flood and debris flow*, pp. 260-279, Logan, Utah, USA, June 14-15, 1984

O'Brien, J. & Julien, P.Y. (1988). Laboratory analysis of mudflow proprieties. *Journal of hydraulic engineering*, Vol.114, pp. 877-887

O'Brien, J.S.; Julien, P.Y. & Fullerton, W.T. (1993). Two dimensional water flood and mudflow simulation. *Journal of hydraulic engineering*, Vol.119, pp. 244-259

Paronuzzi, P., Coccolo, A., Garlatti, G: (1998). Eventi meteorici critici e debris flows nei bacini montani del Friuli. *ACQUA – Sezione I/Memorie Idrogeologia*, pp.39-50

Pierson, T.C. (2005). Hyperconcentrated flow-transitional process between water flow and debris flow, In: *Debris flow Hazard and Related Phenomena*, M. Jakob & O. Hungr, (Eds.), pp. 159-202, Springer, ISBN 3-540-20726-0, Chichester, UK

Pirulli, M. (2005). Numerical modelling of landslide runout, a continuum mechanics approach, Dissertation, Politecnico di Torino, Torino, Italy

Remaitre, A.; Malet, J.P. & Maquaire, O. (2003). Study of a debris flow event by coupling a geomorphological and rheological investigation, example of the Faucon stream (Alpes-de-Haute-Provence, France), In: *Debris flow Hazard Mitigation: Mechanics,* *Prediction and Assessment*, D. Rickenmann & C.I. Chen, (Eds.), ISBN 978-90-77017-78-4, pp. 375-385, Rotterdam, Holland

Rickenmann, D. (1999). Empirical relationships for debris flows. *Natural Hazards*, Vol.19, pp. 47–77

Santi, P.M. (2008). Introduction to the special issue on debris flow initiated by runoff, erosion, and sediment entrainment in western North America. *Geomorphology*, Vol.96, pp. 247-249

Segre, E. & Deangeli, C. (1995). Cellular automaton for realistic modelling of landslides. *Nonlinear Processes in Geophysics*, Vol.2, pp. 1-15

Skempton, A. & De Lory, F. (1957). Stability of natural slope in London clay, *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp. 378-381, London, UK, August 12-24, 1957

Sosio, R.; Crosta, G. B.; Frattini, P. & Valbuzzi, E. (2006). Caratterizzazione reologica e modellazione numerica di un debris flow in ambiente alpino. *Giornale di Geologia Applicata*, Vol.3, pp. 263–268

Takahashi, T. (1991). Debris flow, *Monograph IAHR*, A.A. Balkema, Rotterdam, pp.63-75

Tecca, P.R.; Armento, C. & Genevois, R. (2006). Debris flow hazard and mitigation works in Fiames slope (Dolomites, Italy). *Transaction on Ecology and Environment*, Vol.90, pp. 15-25

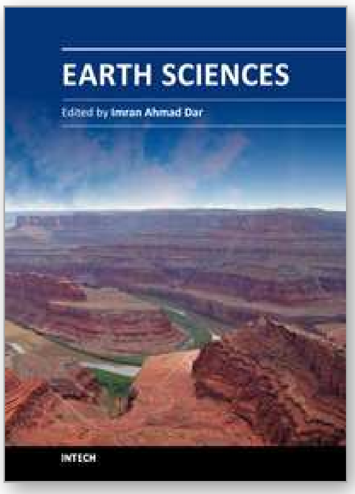
Tropeano, D.; Turconi, L. & Sanna, S. (2004). Debris flows triggered by the 29 August 2003 cloudburst in Val Canale, eastern Italian Alps, *Proceedings of the 10th Internationales Symposion InterPraevent 2004*, pp. 121-132, Riva del Garda, Italy

Varnes, D.J. (1978). Slope movement types and processes. In: *Landslides Analysis and Control (Special report - Transportation Research Board, National Research Council; 176)*, R.L. Schuster & R.J. Krizek, (Eds.), 11–33, Washington DC, USA

Zanon, F. (2010). *Radar hydrology and flash flood event analysis*. Phd. Thesis, Cycle XXII, TESAF Dept. Land, Environment, Agriculture and Forestry, University of Padova, Italy

Whipple, K.X. (1992). Predicting debris-flow runout and deposition on fans: the importance of the flow hydrograph. Erosion, Debris Flows and Environment in Mountain Regions, *Proceedings of the Chengdu Symposium*, pp. 337-345, IAHS Publications No. 209, Chengdu, China, July 5-9, 1992

Winter, M.G; Shackman, L.; Macgregor, F. & Nettleton, I.M. (2005). Background to Scottish landslides and debris flows, In: *Scottish road network landslide study*, M.G. Winter, F. Macgregor & L. Shackman, (Eds.), 12-24, ISBN 0 7559 4649 9, Scottish Executive, Edinburgh, UK



Earth Sciences

Edited by Dr. Imran Ahmad Dar

ISBN 978-953-307-861-8
Hard cover, 648 pages
Publisher InTech

Published in print edition February, 2012

The studies of Earth's history and of the physical and chemical properties of the substances that make up our planet, are of great significance to our understanding both of its past and its future. The geological and other environmental processes on Earth and the composition of the planet are of vital importance in locating and harnessing its resources. This book is primarily written for research scholars, geologists, civil engineers, mining engineers, and environmentalists. Hopefully the text will be used by students, and it will continue to be of value to them throughout their subsequent professional and research careers. This does not mean to infer that the book was written solely or mainly with the student in mind. Indeed from the point of view of the researcher in Earth and Environmental Science it could be argued that this text contains more detail than he will require in his initial studies or research.

Chiara Calligaris and Luca Zini (2012). Debris Flow Phenomena: A Short Overview?, Earth Sciences, Dr. Imran Ahmad Dar (Ed.), ISBN: 978-953-307-861-8, InTech, Available from: http://www.intechopen.com/books/earth-sciences/debris-flow-phenomena-a-short-overview-

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821