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AN INTEGRATED APPROACH TO SIMULATE CHANNALIZED DEBRIS FLOWS FROM TRIGGERING TO DEPOSITION

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ABSTRACT

The purpose of this study, which is currently underway, is the analysis of debris flows from the lithology of the bedrocks (source rocks) that gives rise to the loose material, through the triggering process, to the routing and deposition phases. In particular three methods of analysis have been linked: a geological model, a triggering model that couples the results of a distributed kinematic hydrological model with a critical discharge relationship and a numerical model based on Cellular Automata for the simulation of debris flow routing and deposition. The geological model concerns the catchment lithology and outlines some links between the main lithology forming a basin bedrock and the characteristics of debris flow triggering process. The triggering model, computes debris flow hydrogram which is the input of the routing model. The methodology outlined above was successfully applied to debris flows occurred in a basin located in North-western Alps.

Key Words: *catchment lithology, sedimentary processes, Cellular Automata routing model, hydrological modelling, triggering discharge, North-western Alps*

INTRODUCTION

Debris flows are among the most destructive natural phenomena. The Alpine regions are frequently affected by such a type of mass movements that can cause serious damages to structures and infrastructures.

Several methodologies to predict and modeling their behavior have been proposed in the literature. However models capable to analyze all the involved processes from the critical rainfall, through the triggering, to the debris flow propagation and deposition arequite scarce.

This study is devoted to the development of an integrated method capable to characterize debris flows from the source rock mass generating the loose material through triggering, propagation and deposition modeling. The proposed method is based on the merger of three different approaches: a geological model for basins and sedimentary processes classification, a triggering hydrological model and a routing model

The geological model identifies three basin Groups in the Alpine environment. Each class is characterized by different catchment lithology, basin area/fan area ratio, alluvial fan architecture, debris flow rheology, depositional style and triggering rainfall-characteristics (Tiranti *et alii*, 2008). This method permits to capture the essential features of the flow phenomenon and to address the choice of proper models for the initiation and propagation phases..

The triggering model descends from the method proposed by Gregoretti & Dalla Fontana (2008) to determine the critical runoff that triggers debris flow by channel-bed failure. In particular Gregoretti & Dalla Fontana (2008) compared the runoff simulated by a distributed kinematic hydrological model with the critical discharge value computed by an empirical relationship. If runoff exceeds the value computed by the empirical relationship debris flow starts. The coupling of runoff production at the onset of debris flow and a reliable concentration value for the debris flow routing allows the determination of the water-sediment hydrograph needed as input by the routing model. The input water-sediment hydrograph is estimated through a mass balance involving input runoff and sediment volumes, interstitial water, debris flow sediment concentration and dry bed sediment concentration.

Debris flow propagation is simulated by a Cellular Automata model (Segre & Deangeli, 1995 Deangeli, 2008). The model allows the 3D simulation of solid liquid mixture flows on slopes or channels by taking into account the local properties of the debris material in the computational domain. The site is subdivided into a series of cells. Each cell is characterized by the values of some representative quantities. The system evolution is governed by local rules and depends on the state of the cell and the neighboring cells. The system is synchronously updated at the end of each discrete time step. The Cellular Automata model has been used to back analyze granular flows occurred in northern (Deangeli & Grasso, 1996) and southern Italy (D'Ambrosio *et alii*, 2003), and to forecast possible scenarios in tailing slopes (Deangeli & Giani, 1998).

In the paper are reported the preliminary results obtained by the application of the proposed methodology to a basin located in NorthWestern Alps. The basin is periodically subjected to "viscous" debris flows, being characterised by a debris material with a relatively high clay content.

basin Group	surficial deposits area [%]	fan/basin area [%]	dominant processes	triggering recurrence [years]	minimum triggering rainfall type	main triggering season
1	30	25	CDF	4	storms of high intensity (> 30 mm/h)	late Spring
2	65	3	CDF	1	storms of moderate intensity (> 20- mm/h)	Summer
3	56	4	N-CDF	> 10	alluvial events or supercell storms (up to 50 mm/h)	Autumn and Spring (rarely in Summer)

Tab. 1 - The three catchment lithology Groups in Western Alps (modified after Tiranti et alii, 2008)

BASIN CLASSIFICATION METHOD

According to a recent study conducted on several alluvial fans in the alpine region (Moscariello *et alii,* 2002), the Northwestern Alps basins have been classified by Tiranti *et alii* (2008) into three main typologies of catchment lithology: (1) massive and/or crudely stratified/foliated carbonate rocks (e.g., dolostones, limestones, marbles); (2) fine-grained sheared finely-foliated metamorphic rocks (e.g., calc-schists, shales, phyllades); (3) massive or coarse-grained crystalline rocks or massive quarzite rocks (e.g., granitoids, gneiss, ultrabasites, meta-Qz-conglomerates).

On the basis of these lithological characteristics, the dominant alluvial fan aggradational processes are related to a cohesive debris flow (CDF) and to a non-cohesive debris flow (N-CDF) based on the amount of clay or clay-like minerals and clayey silt produced by different bedrocks. Matrix clay content greater than 5% characterizes the CDF with viscous-plastic rheology; matrix clay amount lower than 5% characterizes N-CDF with collisionalfrictional rheology. In the basins of Group 1 and 2 the CDF are predominant, how-

Fig. 1 - View of the Rio Fosse basin with the watershed contributing to the triggering area

Fig. 2 - The Rio Fosse basin view from alluvial fan apex to the upper part

ever in Group 3 the N-CDF are the main processes. The bedrock nature influences all basin behaviours, such as the sedimentary processes an depositional styles, the frequency of debris flow occurrence and the seasonality, and the alluvial fan architectures.

In Table 1 the main features of the three basin types are summarized.

SELECTED BASIN FOR PRELIMINARY TEST

The Rio Fosse is a northwestern Alpine basin, located near to Bardonecchia locality, in upper Susa Valley (Fig. 1 and 2) The Rio Fosse is a small G1 basin extending over about an area of 1.40 km^2 characterized by a catchment lithology mainly formed by dolostones and limestones, and, subordinate calc-schists (Fig. 3).

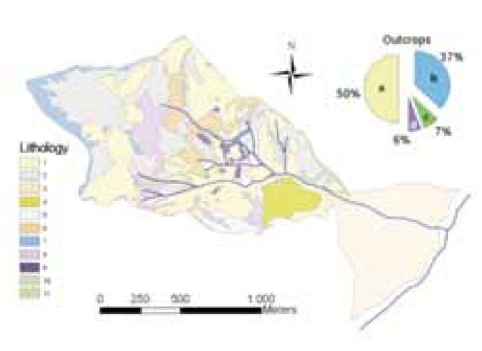

Fig.3 - Geological sketch map of Rio Fosse basin: 1) colluvial cover; 2) talus deposit; 3) alluvial fan deposit; 4) landslide deposit; 5) glacial deposit; 6) karst carbonate breccia; 7) limestone; 8) dolostone; 9) gypsum; 10) calcschist; 11) carbonate schist. In the pai chart the percentages of outcrops are represented: a) 50% are surficial deposits ; b) 37% are carbonate rocks; c) 7% are calc-schists; d) 6% are gypsum

total basin area 1.4 km^2
fan area 0.4 km^2
fan area / basin area 28.6%
main catchment lithology: limestones (75.05%)
dominant process: cohesive debris flow
main depositional style: Rudavoi type (Moscariello et al., 2002)
outcrops percentage 23.01%
elevation range 1340 – 1475 m a.s.l.
average channel inclination 15%
Q max 30 m^3/s
corrivation time 0.29h
outflow coefficient near to 1/1

Tab. 2 - A synthesis of Rio Fosse basin characteristics

The cohesive-debris flows are the dominant processes along the R. Fosse main incised-channel and they are the main processes forming the large alluvial fan. The general basin settings are shown in Table 2.

The triggering area has been identified in a secondary gully where debris deposit is relevant (red outline in fig. 1). This main source area is characterized by a high production of loose material and very steep slopes constituted by dolomitic limestones and by secondary outcrops of gypsum and carbonate breccias.

Generally, the debris flows occurring at Rio Fosse, are triggered if the runoff is able to mobilize the coarser sediments deposited on the surface bed-sediment layer.

The surface layer is somehow armoured through the presence of winnowed partially open-work deposit that cover a clast-supported deposit formed by blocks and boulders in a matrix formed by gravel, sand and clayey-silt. The mobilization of coarse sediments of surficial layer triggers the debris flow and the entrainment of underlying deposits is responsible of the cohesive behaviour of debris flows.

The historical records of this basin showed 20 debris flow events characterized by a low-moderate magnitude since 1868. However, only the data between 1947 and 1973 are forming a continuous historical dataset, because just before this time-interval there was the Second World War, and, many risk mitigation works were made after 1973. Moreover, the main target-object (the "Camping mari e monti") was removed in 1985 (Arpa Piemonte Geological Database, 2010 - http://marcopolo.arpa.piemonte.it /bdge/index.php).

Rainfall data have been provided until 2000 by a rain gauge station, located about 3 km far from the basin. The analysis of these data have shown a relatively high variability in rainfall values (from 55 mm to 0 mm), due to the location of the gauge with respect to the to the Rio Fosse basin. Since 2000 the set up of a meteorological radar system allowed detailed data related to the triggering of debris flows in Alpine environment. The analysis of post event depositions of debris flows are generally qualitative, although for a few events are well documented in terms of area and thickness. For this reason the numerical simulations reported in the following are based on the average value of rainfall data that triggered debris flows. The debris deposition obtained by the numerical analysis are compared with two documented events.

TRIGGERING MODEL

The triggering model is based on the capability of surface runoff descending from cliff and rock walls to mobilize sediments laying on channels incised on the scree at their foot. A number of studies (Griffiths *et alii* 1997; Tognacca *et alii*, 2000; Gregoretti, 2000; Berti & Simoni, 2005; Griffiths et al. 2004; Godt & Coe, 2007; Coe *et alii*, 2008a, 2008b; Gregoretti & Dalla Fontana, 2008; Tecca & Genevois, 2009), relate, in fact, the triggering of debris flow oneither incised channels or on a hillslope, to the erosion power of thewater stream flowing over the sediment bed.

The triggering model is given by the coupling of an hydrological model for runoff simulation and a critical discharge relationship for debris flow initiation. The hydrological model is that used by Gregoretti & Dalla Fontana (2008) for the simulation of runoff triggering debris flow by channel-bed failure.

The model is physically based and distributed and is derived from the KLEM model (Kinematic Local Excess Model) proposed by Cazorzi (2002) and used for computing flash flood hydrograph discharges (Borga et al., 2007; Norbiato *et alii* 2009; Sangati & Borga, 2009; Sangati *et alii,* 2009). The runoff simulation is given by the coupling of SCS method for the determination of excess rainfall or direct runoff with a kinematic method to route it to the outlet. The basin is divided in square cells and for each of these the effective rainfall or runoff production is computed by the Curve Number (CN) method of the Soil Conservation Service. The runoff is then propagated to the basin outlet (the triggering site) along the flow path and the channel network derived from the digital elevation model (DEM) on the basis of the topographic gradient. The channel network is composed by cells with contributing area larger than a threshold value. Different propagation velocities are assigned to the channel network and to the flow paths along slopes. The velocities along the flow paths are varied, depending on the soil characteristics (e.g., runoff velocity on rocky soil is larger than that on a scree). The network velocity is the average velocity in the outlet cross section corresponding to the maximum value of simulated runoff and is assigned by an iterative method: surface runoff is computed using a trial value of the network velocity and using the Gauckler- Strikcler uniform law relationship the average cross section velocity is computed; if the relative difference between the two velocities is larger than 4 %, the simulation is repeated using the computed average cross-section velocity as network velocity. The procedure is repeated until the relative difference between the velocities becomes smaller than 4%.

The hydrograph at the outlet is obtained adding the single cell runoff productions (discharge pulses) that reach the outlet in the same computation time interval.

The critical discharge relationship is that obtained by Gregoretti & Dalla Fontana (2008) using flume-laboratory data for debris flow initiation (Gregoretti, 2000) following the approach of Tognacca *et alii* (2000) and depends on the mean grain size of sediments d_M and bed slope angle θ:

$$q_{CRIT} = 0.78 d_M^{1.5} \tan^{-1.27} \quad (1)$$

where q is the unit width discharge.

Debris flow is triggered if the runoff discharge Qr is larger than $Q_{CRIT} = q_{CRIT}{}^{B}$, being B the channel width in the triggering section. The runoff contributing to debris flow is then all runoff for $t > t_{CRIT}$, time corresponding to *QCRIT* (Figure 4).

The debris flow hydrogram is then computed by a mass balance after assigning the sediment volumetric concentration, C, for debris routing. By definition:

$$\upsilon_D = \frac{V_S}{V_S + Vr + Vw} \quad (2)$$

where V_S is the sediment volume of debris flow; V_r the contributing runoff volume to debris flow; and Vw the interstitial water volume of entrained sediments. The quantity V_w is equal to (1- C*) V_S and then V_S can be computed by equation (2). The value of debris flow discharge Qt is then:

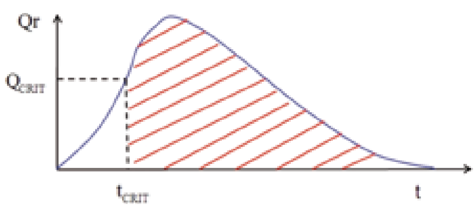

Fig .4 - The runoff contributing to debris flow (shaded area)

$$Qt = \frac{Vs + Vr + Vw}{Vr} Qr \qquad (3)$$

for $t > t_{CRIT.}$ This methodology is currently implemented by the GIS tools AdBToolBox (2010).

ROUTING MODEL

The propagation phase of the debris flow at Rio Fosse basin has been simulated by a 3D numerical code based on Cellular Automata (Segre & Deangeli 1995; Deangeli 2008).

Cellular Automata are mathematical idealizations of physical systems in which space and time are discrete, and physical quantities take on a finite set of discrete values. A cellular automaton consists of a regular uniform lattice (or array), that is usually infinite, with a discrete variable at each site (cell). The state of a cellular automaton is specified by the values of the variables at each site. A cellular automaton evolves in discrete time steps, with the value of the variable at one site being affected by the values of variables at sites in its neighborhood at the previous time step. The variables at each site are updated simultaneously, based on the values of the variables in their neighborhoods at the preceding time step, and according to a definite set of local rules (Wolfram, 1987).

The numerical code was set up to analyze debris flows over a rigid substratum. The debris flow is assumed to be completely mixed. The model does not take into account variations in vertical direction of the debris properties, by adopting a vertically averaged description.

The landslide site is discretized in elementary cells of finite size. In each one the state of the system is specified by the values of some representative quantities.

These include: the height of the impermeable rigid bed r; the amounts of water w and gas g and of granular solids s in the cell. All the contents are given as partial heights (volumes/ base area of the cell), so that the top height in the cell (i) is given by:

$$z(i) = r(i) + w(i) + g(i) + s(i) \qquad (4)$$

The density of the mixture in each cell is given by:

$$\rho(i) = C(i)\rho(i)_s + (1 - C(i))\rho_w \qquad (5)$$

where C is the solid volume concentration, ρs is the solid density and ρ_w the water density.

The lattice geometry implemented in the model is the Cartesian square lattice (b=4) (Figure 5).

Volume and consequently mass conservation are separately imposed for solid and water. Energy and momentum conservation are not enforced here. This is consistent with modeling a process which is dissipative. The assumption that the debris previously in motion can suddenly be stopped within the space of a single cell, depending only on the instantaneous local conditions, is equivalent to the assumption that kinetic energy is readily dissipated, gravity being the main energy source.

Initial conditions for the model are imposed specifying the site topography and the debris distribution at the initial time.

Boundary conditions are easily implemented on any set cells: to realize an open boundary it is just sufficient to force the content of these cells to be always null, while to achieve closed boundaries any resulting out flux is set to zero.

Each cell is connected to a number of its nearest neighboring cells in order to transfer material at each time step. In a 3D field the whole lattice could be considered as a network of elementary slopes (with dips related to the different local topography and debris layers). A two neighbours partition rule for the transfer of debris has been implemented, in order to achieve lattice isotropy. A local slope angle θ (i, v) is defined in the cell (i) for each pair of adjacent neighbours (j_v, j_{v+1}) $(v=1,..b$ modulo b) (Fig. 6).

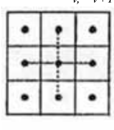

Fig. 5 - Cartesian square lattice.

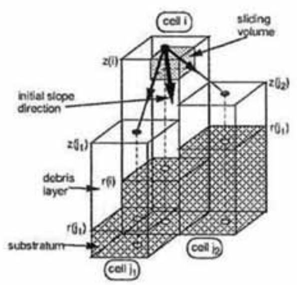

Fig. 7 - Two neighbours partition rule

Evolution rules for the automaton considered the mixture to behave as a Bingham fluid, according to the geological classification of the Rio Fosse basin. The results of the triggering model constitute the input data of the CA model. In particular source cells has been generated in the upper part of the basin. These cells supply a rate of solid water mixture during the first steps of the numerical simulations, according to the total volume predicted by the triggering model. The propagation of elementary flows in each lattice sector (i,v) occurs if:

$$\rho(i) g h(i) \sin\theta(i,v) > \tau_y(i) \tag{6}$$

where $\tau_y(i)$ is the yielding stress of the mixture in cell (i) and *h(i)* is height of the flow at the previous timestep. The cross sectional mean velocity U is :

$$U = \frac{h}{2\mu}\left\{3g\sin\vartheta\left[\left(\rho-\rho_f\right)C+\rho_f\right]\frac{h}{4}-\tau_y\right\} \tag{7}$$

Let quantities q of material flow out of the cell i toward its critical neighbours and evaluate q by putting [z*(i)*-r*(i)*]-[z(j_v)-r(j_v)] as h and θ *(i, v)* as θ in Equation 7. In the model it has been assumed that *q(C, Δz)* are constant during the time step and rely on the first order approximation for small values of the time step Δt. The simplified elementary rate is thus:

$$q_k(i,v) = \Delta t\frac{h(i)^2}{2\mu(i)}\left\{3g\sin\vartheta(i,v)A(i)\frac{h(i)}{4}-\tau_y(i)\right\} \tag{8}$$

where

$$A(i) = \left[\left(\rho(i)-\rho_f\right)C(i)+\rho_f\right]$$

All the computed elementary rates are stored before the simultaneous updating of the lattice. Instantaneous flow rates *q(i)* are evaluated in each cell by vector summing all the incoming flows. The determination of the stoppage travel of a debris flow is still an open problem. A simple local rule that accounts a dynamically corrected slope direction vector *p(i,v)* can be implemented in the model

$$\vec{p}(i,v) \rightarrow \vec{p}(i,v) + \beta\{\vec{q}(i,t-\Delta t) \tag{9}$$

where *q(i,t-Δt)* is the volume inflow in cell (i) at the preceding time step, and β is a parameter of the model that must be properly calibrated.

THE SIMULATION OF DEBRIS FLOWS IN RIO FOSSE BASIN

At this preliminary stage of the work, it has been assumed the triggering area of debris flows is the outlet of the watershed basin whose boundary are reported in Figure 1. In that area, debris deposits are laying on the channel bottom while the upper part is characterized by larger slope values and the quantity of sediments constituting the bed is not enough for debris flow formation. The channel width is b = 4 m, and the bed slope is $\tan\theta = 0.4$. The sediments showed the following a grain-size features: $d_{90} = 50$ mm, $d_{60} = 18$ mm, and $(d_{84}/d_{16})^{0.5} = 26.7$. The average diameter, based on the average value of each soil class is dM = 0.015 m.

On the basis of Gregoretti & Dalla Fontana (2008) analysis of critical runoff in which 19 of 20 peak times of simulated runoff corresponding to the occurred and documented debris flows were close to the triggered times, the triggering rainfall is assumed to be the daily non-stop rainfall producing the highest runoff value.

The runoff simulation was carried out using the CN values shown in Table 3 and a roughness coefficient K_s = 9 $m^{1/3}$/s according to Gregoretti & Dalla Fontana (2008). The critical unit width discharge computed by eq. (1) is 0.005 m^2/s that is 0.02 m3/s. The saturation discharge computed according to the methodology proposed by Gregoretti & Dalla Fontana (2008) is 0.08 m^3/s and then the triggering discharge is 0.1 m3/s. The largest value of simulated runoff is Q = 0.4425 m^3/s and then the triggering discharge is Q = 0.3425 m^3/s.

The runoff volume contributing to debris flow (Fig. 4) is 10100 m^3 and the corresponding debris flow volume is 21400 m^3 (sediment volume = 7490 m^3) has been computed by adopting a sediment volumetric concentration C = 0.35.

The basin has been discretized in elementary cells. The volume of the solid water mixture, calculated on the basis of the watersediment hydrograph has been subdivided between the source cells.

The consequent rates of moving material from these cells to the neighbouring cells of the model last until the complete depletion of the calculated volume. The transfer of material between the cells occurs ac-

	Rock	Scree	Pasture	Pasture and rocks	Wood
CN	90	60	65	70	30
Slope velocity	0.3	0.1	0.2	0.15	0.03

Tab. 3 - The entire list of recorded debris flow events occurred in the basin

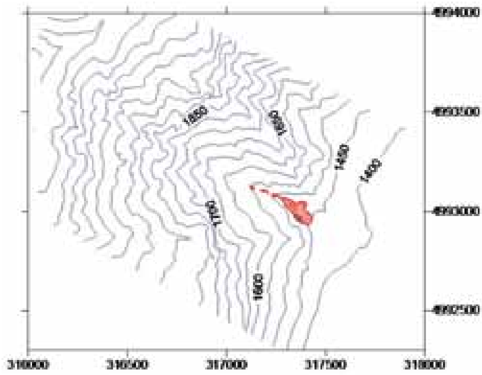

Fig.7 - Results of the numerical analysis for the phase of propagation of debris flows in the Rio Fosse basin

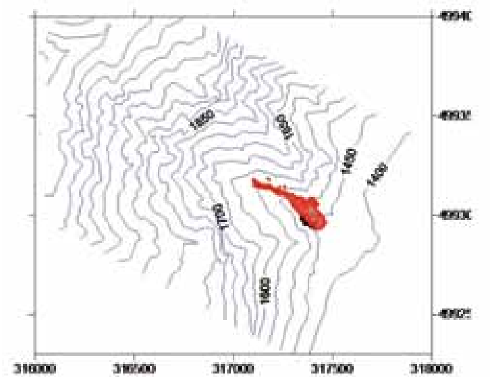

Fig.8 - Deposition of the debris flows occurred on July 1994

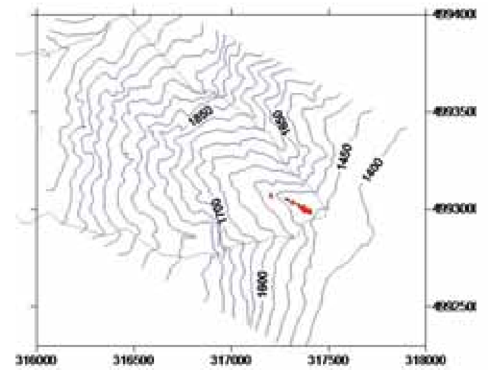

Fig. 9 - Deposition of the debris flows occurred on September 2006

cording to equations 7 and 8. The input parameters have been estimated on the basis of literature data, for similar types of rocks.

Figure 7 reports the final results of the numerical simulation. By a general point of view these results seem to be consistent with the characteristics of debris flows in the Rio Fosse basin.

Figures 8 and 9 show the deposition features of the two debris flow events occurred on July 1994 and September 2006 respectively. Although the rainfall data (both recorded by the rain gauge stations of Bardonecchia) were not so different deposition volumes of these two events were definitely different. Probably the main reason of this behaviour can be attributed to the availability of debris material and the serviceability of the small dams located in the upper part of the channel.

The comparison between Figure 7 and Figures 8 and 9 show that the debris flow simulated on the basis of the characteristics of several debris flows occurred in the Rio Fosse basin, by considering the triggering area reported in Fig. 1 and by assuming, on the basis of the geological model, a viscous behaviour of the mixture, exhibits depositional features in agreement with the reported real cases.

CONCLUDING REMARKS

The paper has reported the first results of the application of a comprehensive methodology for the analysis of debris flows from the lithology of the bedrocks (source rocks) that gives rise to the loose material, through the triggering process, to the routing and deposition phases.

The proposed methodology, based on the link between a geological model for basins and sedimentary processes classification, a triggering hydrological model and a routing model, has been applied to a basin located in the North-western Alps. The basin is periodically subjected to "viscous" debris flows, being characterised by a debris material with a relatively high clayey silt content. The results of this first application show a relatively good agreement with the available data of debris flows occurred in the basin.

Because of the promising results in the future the methodology will be improved and extended to the other two lithological Groups of material by implementing appropriate constitutive laws.

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