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AN INTEGRATED APPROACH FOR DEBRIS FLOW HAZARD ASSESSMENT - A CASE STUDYON THE AMALFI COAST - CAMPANIA, ITALY

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ABSTRACT

In this work, a multidisciplinary study is presented in which potential debris flow events are studied from their beginning to their end. The case study is located on the Amalfi Coast where historical events of debris flow are well documented in 1910, 1924 and 1954. An integrated approach was used for the geomorphology and geo-pedology of volcanic deposits. The matches found between morphotypes, depositional and pedological processes and soil characteristics made it possible to develop a detailed map of the soil deposits which was then used to estimate the geographical distribution of the parameters relevant in the stability analysis. The modeling of debris flow initiation process is carried out through a stability analysis of the soil after a rainfall characterized by a given intensity and duration. The debris flow volume corresponding to a given return period is subsequently obtained. The propagation of this volume is then simulated through a commercial, two dimensional model (FLO2D). Both modeling approaches, for the initiation and the propagation processes, are tested by comparing them with a historical event in 1954. The integrated procedure described makes it possible to draw up maps of debris flow intensity corresponding to assigned return periods. These elements may be easily elaborated in order to draw up debris flow hazard and risk maps.

Key words: *debris flow, hazard map, modelling*

INTRODUCTION

The governmental organizations in charge of protection against natural risks, usually develop the strategies for risk mitigation on the basis of a risk map displaying the different natural risks affecting the territories studied. A risk map is obtained through the overlaying of a hazard map with a vulnerability map. The realization of a hazard map, that requires the estimation of the event intensity along with its probability, is the most difficult task. In the case of debris flows, a complete and trustworthy methodology has yet to be developed. The intensity of debris flows, in a particular point of the land surface, may be evaluated by the means of the depth and velocity of the flow. Therefore, a correct hazard estimation passes through the estimation, in each point of the studied area, of velocity and depth along with the associated probability of occurrence.

Debris flow phenomena are generally not frequent enough to allow for a direct estimation of probability on the basis of the observation of past events. Therefore, the probability of an event, with a given intensity, has to be derived from the estimation of the probability of the variables contributing to the event formation.

Assuming the land characteristics do not change over time, the triggering variable is the rainfall. The rainfall with a given intensity and duration, and given probability, should be coupled with the consequent mobilization of soils and formation of debris flows

Simple land stability models, available in literature (Montgomery & Dietrich, 1994) are “static” and

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allow for the estimation of the effect of a rainfall with a given intensity and indefinite duration. This means that the association of a probability to the occurrence of this rainfall is not feasible and as a consequence the hazard estimation is not realizable. In this work, an attempt has been made to overcome this difficulty.

Once the volumes of the soils mobilized by the rainfall with a given probability have been estimated, the propagation of the solid liquid mixture may be simulated with a two dimensional mathematical model (O'Brien, 2007, Medina *et alii*, 2008) and the event intensity distribution may be evaluated in the alluvial fan.

Thus, an intensity map can be developed for each probability, with it subsequently being possible to draw up a hazard map.

In order to allow for a simple and safe use of the developed methodology, simulation models have been chosen that have been widely tested in different geological contests, that are largely documented in literature and that are available as open source or commercial software.

In order to perform a trustworthy estimation of mobilized soil volume, land stability model requires a detailed map of soil deposit characteristics. In the present work a rapid and economic method for soil deposits mapping is proposed

Both modeling approaches, for the initiation and the propagation processes, are tested by the back analysis of a past event.

STUDY AREA

The catchment area of Torrente Sambuco has an areal extent of approximately 6.5 square kilometers and covers the municipalities of Ravello and Minori (Amalfi coast, province of Salerno - Fig. 1).

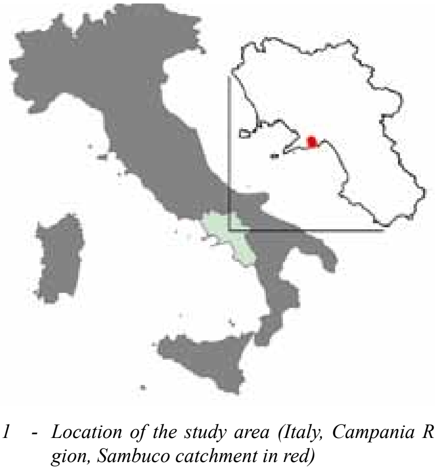


Fig. 1 - Location of the study area (Italy, Campania Region, Sambuco catchment in red)

The northern part of the basin is mountainous and has a rough morphology with an elevation varying between 800 and 1000 meters above sea level. Proceeding southward, towards the coastal area, the maximum elevation of the relief gradually decreases until it reaches 200 meters.

The mountainsides of the basin have very high slopes and are often interrupted by sub-vertical walls, the most widespread slope is between 30° and 45°. These areas are used predominantly for forestry (hardwood forests of holm-oak and chestnut) with areas of Mediterranean bush. The foothills and lower slopes (with a gradient between 17° to 30°), are mostly terraced for agriculture (vineyards, citrus orchards and mixed orchards). The urbanized area coincides with the final stretch of the T. Sambuco valley towards the alluvial fan and the narrow coastal strip

METHODOLOGY KEY POINTS

CHARACTERIZATION OF THE SOIL DEPOSITS

The deposits covering the slopes of the studied area are constituted by ashes, pumice and scoriae, and are defined, from a geological point of view, “pyroclastic fall”. This type of deposits mainly derives from the eruptive activity of the Somma-Vesuvius volcano (eruptions immediately before, and after the in 79 A D, until the last one in 1944).

These deposits are layered, rehandled and often profoundly weathered. They overlay a large portion of the reliefs especially in more morphologically depressed areas. It is well known that in the Campania region, as well as different Italian mountain systems (Iamarino & Terribile, 2008), the weathering and the pedogenetic processes of such deposits have produced soils with peculiar characteristics, defined “andic properties” (Keys to Soil Taxonomy, 2006).

Andic soils have a unique set of morphological, physical and chemical properties that can be attributed to the presence of noncrystalline and/or poorly ordered clay minerals such as allophone, imogolite, ferrihydrite and Al/Fe- humus complexes (Parfitt, 1990; Shoji *et alii*, 1993). These soils, classified as Andosols, are characterized by large porosity, elevated water retention, a friable structure, variable-charge minerals, large organic matter and thixotropy properties. The andic characteristics are often distributed in a non-homogeneous way into the soil horizons, resulting in a marked vertical anisotropy in its physical and chemical properties. Mainly due to some of their common properties, andic soils have high soil water contents, often equal to or even higher than its dry weight (Basile *et alii,* 2003).

The soils of Sambuco catchment has a complex sequence, due to the deposition of volcanic materials that have covered the carbonaterocks at different times, which has lead to interrupting the previous pedogenetic cycles (as witnessed by buried soils).

The typical horizons sequence of a pedological profile in the study area is: A-Bw-C-2Bwb. However, this sequence is often delayed by erosion and post-depositional processes.

The contact between the limestone and volcanic soil is generally abrupt. However, in some places, between Andosols and limestone, the presence of ancient soils strongly argillified (Alfisols) can be observed, which fill pockets and fractures in carbonate rocks. This arrangement results in a marked variability of the soil properties as well as the absence of a single soil stratigraphy reference. Consequently, one major problem in drawing up a detailed map of the deposits, and therefore a good prevision of possible instable soil volume, is in identifying the most appropriate method for defining the spatial distribution of the different soil typologies.

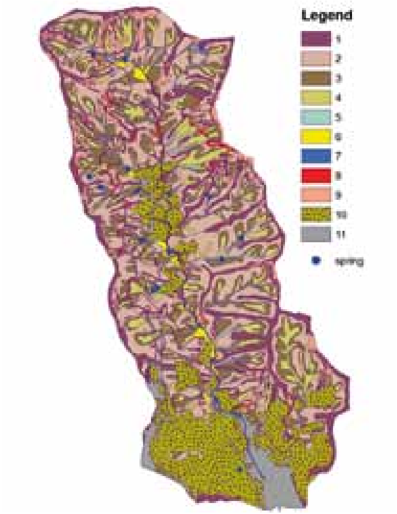


Fig. 2 - Integrated mapping of soils and morphotypes (simplified label description in Table 1)

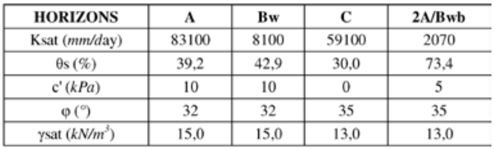
In this study, the problem has been addressed by the well known correspondence between surface geomorphology and the spatial variability of soils and deposits; it has been scientifically described by various authors (Conacher & Dalrymple, 1977; Birkeland, 1984), opening the way for rapid and economic methods of mapping soils on large areas, not otherwise achievable, especially in mountainous areas.

An integrated mapping (scale 1:2,000) of the geo-pedological and geomorphological characteristics of the area concerned was therefore carried out, based on the observed correlation between the morphotypes, pedogenetic conditions and soils detected (Fig. 2). The methodological approach used for the integration of the geomorphology and pedology follows, in large part, as indicated in Guida *et alii* (2007), for similar near areas.

Once the territory has been divided into morphological units and associations of soils, with each one being characterized by a profiletype representative (stratified pyroclastic sequences where present), an attempt was made to assign characteristic hydrological and geotechnical parameters to the four most common horizon profiles (see Table 2). This procedure was carried out on the basis of detailed studies, made by some authors, on the physical, mechanical and hydrological characterization of the different layers that make up the pyroclastic covers of the Campanian relief (Bilotta *et alii*, 2005; Basile *et alii*, 2003).

Morphotype	Typical Profile	Layers	Horizon type	Horizon thickness/ Profile thickness (%)
1- Ridge	1	1	A	100
2 - Convex slope	2	4	A-Bw-C-2A/Bwb	20 - 30 - 20 - 30
3 - Concave slope	3	4	A-Bw-C-2A/Bwb	20 - 30 - 20 - 30
4 - Z.O.B. and hollow	4	2	A-Bw	15 - 85
5 - 'Vallecola' a V	-	1	Limestone debris in pyroclastic matrix	100
6 - Alluvial fan and talus	6	2	A - Bw	10 - 90
7 - Riverbed and valley bottom	-	1	Gravel in sandy matrix pyroclastic	100
8 - Scarp	-	0	Bare rock	
9 - Denuded area	-	0	Rock with thin discontinuous soils	
10 - Terrace area	-	1	Rehandled soils	100
11 - Inhabited and roads	-	-	-	

Tab 1 - Outline of the correspondence between morphotypes and typical soil profiles



HORIZONS	A	Bw	C	2A/Bwb
Ksat (*mm/day*)	83100	8100	59100	2070
θs (%)	39,2	42,9	30,0	73,4
c' (*kPa*)	10	10	0	5
φ (°)	32	32	35	35
γsat (*kN/m³*)	15,0	15,0	13,0	13,0

Tab. 2 - Hydrological and geotechnical characteristic parameters assigned to the horizons (typical profile 1, 2, 3, 4, 6)

ESTIMATION OF DEBRIS FLOW INPUT HYDROGRAPH

The widespread used SHALSTAB model (Montgomery & Dietrich, 1994) has been employed to simulate the land instabilities caused by a given rainfall. The SHALSTAB model assumes that the precipitation has a constant intensity for a time interval sufficiently long to reach a stationary underground water flow. This hypothesis has two important consequences. The first is that, when performing a back analysis, instability areas are usually overestimated. This happens because the triggering rainfall is usually shorter than the time necessary for reaching the stationary conditions and therefore the effect of a longer rainfall is simulated instead of the real one. The second consequence of the cited hypothesis is the difficulty of defining the return period associated to a given soil instability scenario.

In order to overcome these limitations, in the present work, a rough estimation of the rainfall duration is given, assuming that it is equal to time necessary for the soil to reach steady state conditions (s). This time is assessed by an extremely simplified volume balance between input and output water flux through the basin (Papa *et alii*, 2010):

$$\tau_s = \frac{1}{n}\sum_{i=1}^{n}\frac{a_i}{b_i}\frac{\theta_{s_i}}{K_i\cos\alpha_i\sin\alpha_i} \qquad (1)$$

where n is the total number of computation cells, a_i is the contributing area to the cell *i, b* is the width of the cell along the contour line, *K* is soil permeability, a is the slope and s is the water content at saturation.

According to this equation, the interval time required to reach steady conditions, for the Sambuco basin closed at the outlet, is 75 days. For the sub-basins closed at their junction with the main valley, the time intervals are smaller, varying with the size of the sub-basin and its average slope, and falling in a range between 15 and 51 days.

Debris flow origins mainly in the first order little sub-basins; with reference to these basins, the SHALSTAB simulation of land stability condition has been performed after a rainfall having duration equal to 15 days.

The shape of the flow hydrograph has been assigned trough the following relation:

$$Q(t) = Q_p \cdot \left(\frac{t}{t_p}\right)^2 e^{2\left(1-\frac{t}{t_p}\right)} \qquad (2)$$

where Q_p is the peak discharge of the hydrograph and t_p is a characteristic time length. The total debris flow volume (W) and the peak discharge are related as follow:

$$Q_p = \frac{4 \cdot W}{e^2 \cdot t_p} \qquad (3)$$

The total debris flow volume is assumed equal to the instabilized soil volume, and tp has been estimated through taking into account the length path of the farthest instabilized pixel from the control section, and the mean velocity of the flow along this path.

The soil concentration of the mixture is estimated as the complement to 1 of the averaged instabilized soil deposits porosity

SIMULATION OF DEBRIS FLOW PROPAGATION

The propagation of debris flows has been simulated through the widespread used commercial code FLO-2D (O'Brien, 2007). This model solves the Saint-Venant equations in the two dimensional frame (Mahmood & Yevjevich, 1975). The FLO-2D model makes it possible to simulate the presence of buildings, by limiting the flow that can cross the computational cell as well as the presence of roads, which are instead preferentially paths

The flow resistance is described through a rheological equation (O'Brien & Julien, 1988, 1993; O'Brien, 2007) declinable for different kinds of mixture:

$$\tau = \tau_y + \eta\left(\frac{du}{dy}\right) + \chi\left(\frac{du}{dy}\right)^2 \qquad (4)$$

The first term (τ_y) is the threshold stress that must be overcome in order to give place to the flow. This term takes into account both the cohesion, linked to the presence of fine sediments, as well as the Mohr-Coulomb stress. The second term represents the stress due to viscosity, which, according to Newton's law, has a trend proportional to strain rate (*du/dy*) through a viscosity coefficient (η). The third term is the sum of the effects of the collisions between particles and the turbulent stress. Both these components depend on the square of the strain rate (Bagnold, 1954; Takahashi, 1991; Egashira *et alii*, 1997) and are expressed through the coefficient χ.

The shear strength (τ_y) and viscosity (η) depend on solid concentration (C) through the following equations

$$\tau_y = \alpha_2 e^{\beta_2 C}$$
$$\eta = \alpha_1 e^{\beta_1 C} \qquad (5)$$

where α_1, β_1, α_2 e β_2 are parameters depending on the mixture properties.:

This formulation can be specified to describe the behaviour of the mixtures involved in the debris flows of the Campanian Apennine. These mixtures have a significant fine content of clay and silt (about 20%) and at the same time, a high content of coarse sediments, with sands and gravels. This particular composition is responsible for a particular rheological behaviour that is influenced both by the presence of fine particles, giving rise to a threshold-type cohesive effort and a high viscosity, as well as the presence of coarser sediments that give rise to the collisional behaviour

Laboratory tests (Papa & Martino, 2007 Martino, 2003), were carried out on samples taken in areas affected by debris flow phenomena in May 1998 in the town of Sarno. The mixtures involved in these events have the same main characteristics, genesis and granulometry of the Amalfi Coast soils, and therefore the results of the rheological tests performed on the samples collected in the Sarno area may be used in characterizing the debris flow mixtures of the Amalfi Coast basins, such as the Sambuco basin.

The rheological tests showed a shear thickening behaviour, described in detail by a Herschel Bulkley equation (Coussot, 1996) with the exponent of strain rate being equal to 1.7..

In order to use the FLO-2D code, the rheological equation should be put in the form of equation (4). This is possible from experimental data, although this equation gives rise to a lower agreement with the experimental data than the Herschel Bulkley type. For each test, the solid concentration is known and the shear stresses are measured at different strain rate values. For each test, it is then possible to estimate the quadratic equation of the type of equation (4) that best approximates the experimental trend. The curves obtained and their equations are shown in Figure 3.

Once given the regression lines of Figure 3, the curves of equation (5) that best approximate the parameters can be estimated. The regression curves obtained are shown in Figure 4.

The estimated values for the resistance parameters of equation(5) are reported below:

$$\alpha_1 = 0{,}0145 \ \ Pa$$
$$\beta_1 = 8{,}3$$
$$\alpha_2 = 0{,}0134 \ \ Pa$$
$$\beta_2 = 14{,}1$$

The depth integrated law resistance in non-dimensional form is (O'Brien & Julien, 1993):

$$S_f = \frac{\tau_y}{\gamma_m h} + \frac{K \eta V}{8 \gamma_m h^2} + \frac{n_{td}^2 V^2}{h^{4/3}} \qquad (6)$$

where S_f is the energy gradient, γ_m is the specific weight of the mixture, h is the flow depth, V is the flow velocity, n_{td} is a generalized Manning coefficient (O'Brien, 2007) and K is a coefficient that takes into account the fact that under real scale conditions, the flow resistance is increased by the presence of obstacles and macro-roughness as well as by the effect of

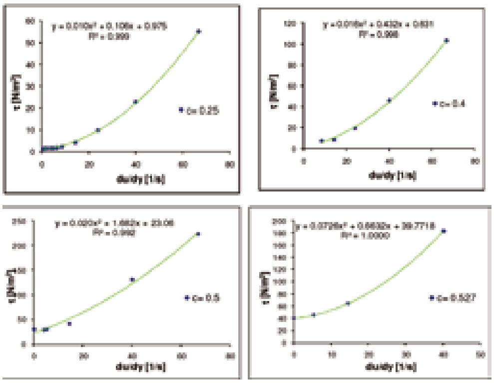


Fig. 3 - Regression curves of the experimentally measured shear stress and shear rate

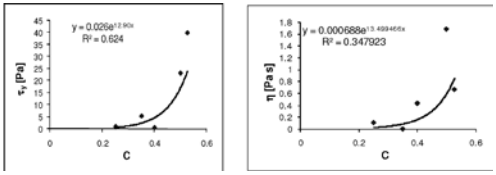


Fig. 4 - Regression curves of the resistance parameters depending on the solid concentration of the mixture

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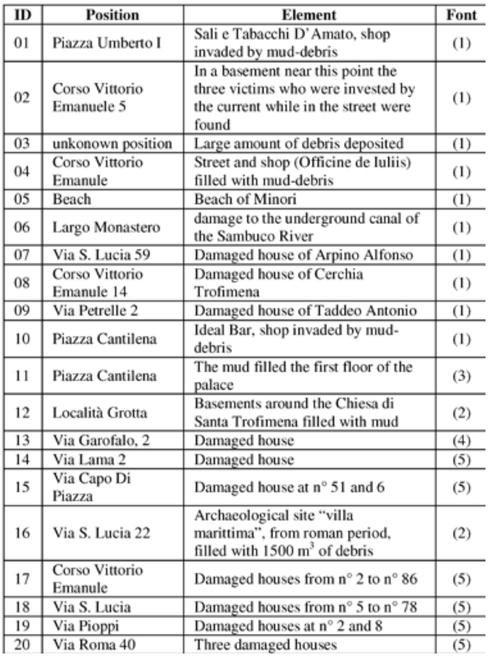
the compact cross sections. As noted by Martino & Papa, 2008, the restraining effect that occurs in the in-channel flux is responsible for a significant reduction in flow velocity. Although the estimate of *K*, is crucial for a correct characterization of the motion, a rational criteria for its assessment is still not available. The authors of the FLO-2D code propose empirical relationships to calculate the parameters ntd and *K* depending on the Manning's coefficient (O'Brien, 2007). In the present work, the Manning coefficient was estimated according to the type of sliding surfaces, using literature values (Chow, 1959).

Being that all the rheological parameters had already been obtained from other tests or literature, it was not necessary to calibrate the model in order to estimate the significant parameters.

BACK ANALYSISI OF 1954 DEBRIS FLOW EVENT

HISTORICAL DATA

On 25 October 1954, on the Amalfi Coast and in the city of Salerno, several detachments from the slopes occurred, resulting in waves of debris flow that also invested the village of Minori, causing extensive damage and three deaths. The debris flow covered part of the historical centre of the village, damaged many houses, as well as carried large amounts of debris onto the beach.



ID	Position	Element	Font
01	Piazza Umberto I	Sali e Tabacchi D'Amato, shop invaded by mud-debris	(1)
02	Corso Vittorio Emanuele 5	In a basement near this point the three victims who were invested by the current while in the street were found	(1)
03	unkonown position	Large amount of debris deposited	(1)
04	Corso Vittorio Emanule	Street and shop (Officine de Iuliis) filled with mud-debris	(1)
05	Beach	Beach of Minori	(1)
06	Largo Monastero	damage to the underground canal of the Sambuco River	(1)
07	Via S. Lucia 59	Damaged house of Arpino Alfonso	(1)
08	Corso Vittorio Emanule 14	Damaged house of Cerchia Trofimena	(1)
09	Via Petrelle 2	Damaged house of Taddeo Antonio	(1)
10	Piazza Cantilena	Ideal Bar, shop invaded by mud-debris	(1)
11	Piazza Cantilena	The mud filled the first floor of the palace	(3)
12	Località Grotta	Basements around the Chiesa di Santa Trofimena filled with mud	(2)
13	Via Garofalo, 2	Damaged house	(4)
14	Via Lama 2	Damaged house	(5)
15	Via Capo Di Piazza	Damaged house at n° 51 and 6	(5)
16	Via S. Lucia 22	Archaeological site "villa marittima", from roman period, filled with 1500 m^3 of debris	(2)
17	Corso Vittorio Emanule	Damaged houses from n° 2 to n° 86	(5)
18	Via S. Lucia	Damaged houses from n° 5 to n° 78	(5)
19	Via Pioppi	Damaged houses at n° 2 and 8	(5)
20	Via Roma 40	Three damaged houses	(5)

Tab. 3 - Evidence of the effects of the 1954 event

Table 3 shows a list of the documentary sources that have been consulted in order to both estimate the main characteristics of the event as well as obtain useful data for the validation of the simulation models. The documentary sources are classified as: (1) photographs; (2) publication of historical studies (Buonomo & Gambardella, 2004); (3) video documentaries (De Iuliis, 2004); (4) documents claiming damages by individuals and companies; (5) list of homeless families

The location of the different documentary sources is shown in Figure 7.

The reconstruction of the tracks of the landslide is part of another study that is currently underway, aimed at mapping all the landslides in the entire area affected by the flooding of 1954.

COMPARISON AMONG OBSERVED AND SIMULATED TRIGGERING AREAS

The reconstruction of the meteorological event made by the Servizio Idrografico e Mareografico Italiano (SIMI) has provided the map of isohyets that intersected with the Sambuco basin which gives, for the daily precipitation of the 25th of October, an average of 321 mm. In Figure 5, the unstable areas assessed by the model SHALSTAB, are represented, as a result of a precipitation intensity of 321 mm/day. In the same figure, the landslide scars reconstructed on the basis of field investigations are also plotted. It is also worth noting that the simulation greatly overestimates the event. The simulated area affected by the landslide is 33.6% of the total area of the basin, while the area actually affected was equal to only 2.8%. This result is not surprising given the consideration discussed above. The simulation was repeated taking into consideration the cumulative precipitation during the 15 days preceding the event, resulting in an average intensity of 22 mm/day. The results are shown in Figure 6. In this case, the simulated landslides cover a total area of the 2.8% of the basin.

However, there is a marked difference in the shapes of the landslide, in the simulations, with the instable areas being made up of many distributed pixels, while in the real case the areas are more compact. These differences can be attributed to the fact that the

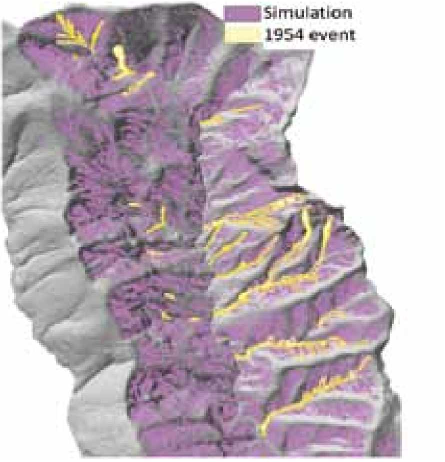


Fig. 5 - Landslide of 1954, comparison among observations and the simulation obtained with a triggering rainfall intensity of 321 mm/day

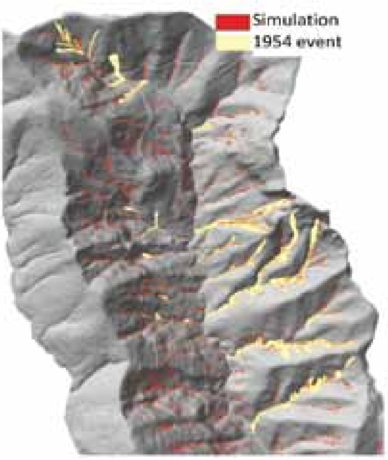


Fig. 6 - Landslide of 1954, comparison among observations and thesimulation obtained with a triggering rainfall intensity of 22 mm/day

single pixel, that is unstable in the simulation, is stable in reality, due to the presence of adjacent stable pixels. Moreover, an unstable cluster of pixels that begins to move may involve other adjacent pixels, though these appear to be stable in the simulations. These processes are not reproduced by the procedure outlined here. Further studies and investigations are needed in order to establish the criteria to describe them. However, when aiming to the simulation of the downstream propagation of a debris flow only the total triggered volume is necessary, regardless to the shape and distribution of the instabilized areas.

Based on the analysis carried out, it appears that the total volume triggered by a steady rainfall with intensity equal to the average of the cumulated rainfall of duration estimated by equation (1), despite the limitations related to the extreme simplicity of the approach, gives significantly accurate estimates which can be used for technical applications.

COMPARISON AMONG OBSERVED AND SIMULATED FLOWS

At the time of the event the Sambuco stream flowed into the centre of the village of Minori, along the houses and the main street (position ID 4 in Fig. 7), the downstream part the river flowed into an underground canal (beginning in ID 6) until reaching the sea outlet. In the simulations, it has been assumed that the underground canal was completely clogged with sediments, due to its small section. This hypothesis is substantiated by testimonies relating to it being blocked.

The simulations presented here were carried out on a 10 m computational grid, with a higher resolution not being possible due to numerical stability reasons.

A first simulation was carried out assuming that the total volume mobilized contributed to form a single surge (single impulse). In this case, the solid-liquid input hydrograph is characterized by a total volume of 300,000 m^3 and a peak flow of 180 m^3/s. Figure 7 shows the total area invaded which appears to be higher than the observed one.

According to witnesses (Buonomo & Gambardella, 2004), therewere several waves. Therefore, the propagation of the hydrograph resulting from the landslide with the largest volume (63,000 m^3) was also simulated. In this scenario (several impulses), the peak flow is 58 m^3/s. The effects, in terms of maximum envelope of flow depths for each computational cell, are shown in Figure 7.

In this case, the agreement between the simulation and observations is very good. All the positions at which debris flow effects have been documented result being affected by the simulated debris flow (see Tab. 3).

The only position (ID 14) that is not touched by the simulated debris flow, while affected by the real one, is in a small road that cannot be reproduced on the used10 m grid.

The simulation reproduces the volume of 1500 cubic meters of material, which had filled the depressed area at the archaeological site. The thickness of the debris that according to witnesses had filled the ground floor of buildings (ID 11) is also well simulated. The

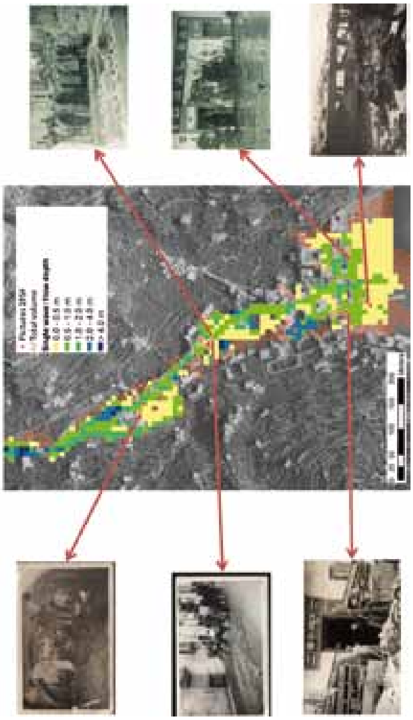


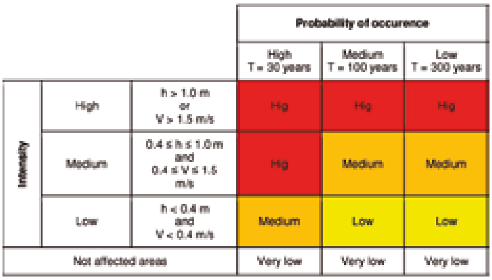
Fig. 7 - Simulation of the total debris flow area in the "single impulse" scenario and envelope of maximum flow depths in the "several impulses" scenario

flow velocities seem consistent with the magnitude of effects observed. These indeed have values of approximately 2 m/s along Corso Vittorio Emanuele, where the debris flow produced the largest amount of damage to buildings, with values of the order of 1 m/s in areas adjacent to the Corso Vittorio Emanuele, and values under 0.5 m/s in the remaining part of village where there are documented deposits but without any damage to the structures.

HAZARD MAP

Several criteria for the classification of debris flow intensity and hazard, are available in literature (Hürlimann *et alii*, 2008). In the present work, the criterion proposed by Rickenmann (2005) has been used, with a minor modification (see Fig. 8)

Once fixed the return period (T) and the rainfall duration (15 days), the intensity of the triggering rainfall can be easily estimated from the Intensity-Duration-Frequency curves relevant for the Sambuco catchment. The volumes of possible debris flows have been consequently estimated, with the procedure described above.



			Probability of occurence		
			High T = 30 years	Medium T = 100 years	Low T = 300 years
Intensity	High	h > 1.0 m or V > 1.5 m/s	Hig	Hig	Hig
	Medium	0.4 ≤ h ≤ 1.0 m and 0.4 ≤ V ≤ 1.5 m/s	Hig	Medium	Medium
	Low	h < 0.4 m and V < 0.4 m/s	Medium	Low	Low
Not affected areas			Very low	Very low	Very low

Fig 8 - Hazard matrix adapted from Rickenmann (2005). T is the return period of the event

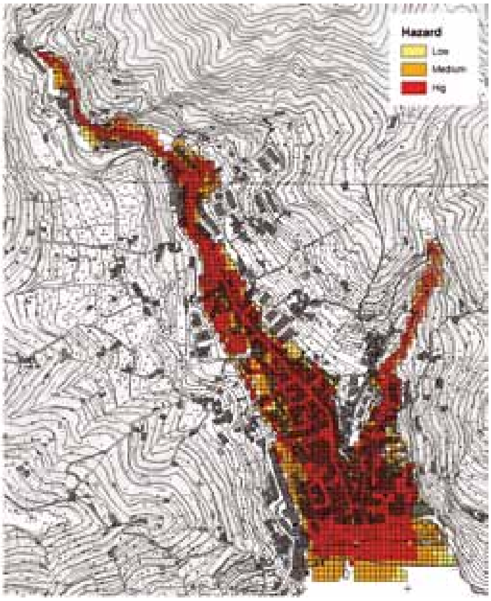


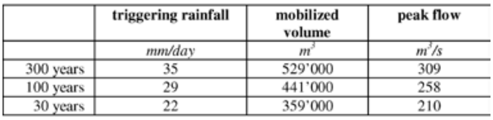
Fig. 9 - Calculated hazard map

Many different surges may develop, as it was observed in the 1954 event, but it is not possible to make a reliable prevision of this behaviour. Thus, for the sake of safety, a single surge event was considered.

All the relevant parameters of the calculation are summarized in Table 4.

DISCUSSION AND CONCLUDING REMARKS

Debris flow hazard mapping requires the development of various models in order to assess the effects of precipitation with assigned return period in terms of flow depths and velocities in the flooded area. In particular, the system considered in this study consists of four parts: the mapping of soil characteristics, the modeling of DF initiation, the modeling of DF propa-



	triggering rainfall	mobilized volume	peak flow
	mm/day	*m^3*	*m^3/s*
300 years	35	529'000	309
100 years	29	441'000	258
30 years	22	359'000	210

Tab. 4 - Relevant parameters of the estimated events used to develop the hazard map

gation, the intersection of event probability (assessed by the triggering rainfall return period) with the event intensity (resulting from the propagation model)

With the aim of providing a debris flow hazard mapping methodology for technical application, the models selected for the simulation of triggering and propagation processes are both widespread used models that have been tested in many different geological contests. In order to allow for a wide use of the developed system, simulation models have been chosen that are available as open source or commercial software.

The routines employed for the simulation of DF formation and DF propagation have been previously tested by comparison with an historical event, reconstructed on the basis of historical documentation. The model used for the prevision of land instabilities gave simulated triggering areas very different from the observed ones. Nevertheless the total triggered volume was estimated accurately. Some other method needs to be developed if the delimitation of potentially unstable slopes is required. But when, like in the present case, the object of the study is the prediction of extension and magnitude of invaded areas, only the total triggered volume is necessary, regardless to the shape and distribution of the instabilized areas. In these circumstances the employed model seems to be appropriate.

The runout process simulation has provided fairly good results. After the testing of the two modelling methodologies, the entire system has been applied for the drawing up of hazard maps

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