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Comparison of different methods for debris-flow run-out analyses. Insights from the case of Nus (Valle D'Aosta, Italy)

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ABSTRACT - The presented study compares some methods for assessing potential debris-flow paths (and, thus, related spatial hazard) on Alpine alluvial fans in order to evaluate their potential applications. The proposed methods range from empirical to numerical approaches. In particular, the different techniques were used to back-analyse a debris-flow event; their reliability was then assessed by comparing the results with the actual mapped effects of the reference event.

The investigated area is located in the western Alpine arc, in the municipality of Nus (Aosta, Italy), which was hit by a major flood on October 2000. Slope phenomena were dominantly of the debris-flow type and affected a wide portion of Nus, which lies on an alluvial fan in the catchment area of the St. Barthélemy river.

The main effects of the debris-flow (in terms of invaded areas, erosional and depositional zones) were surveyed and mapped. Such an activity, together with the availability of detailed maps of the event produced by Civil Protection authorities, allowed us to calibrate the input parameters of each adopted methodology. Not much confidence should be put in the results of empirical methodologies as they can be significantly dependent on hardly determinable input parameters, or underestimate the level of hazard and be excessively dependent on previous phenomena. The comprehensive hydraulic methodology produced more reliable results, even if the quality and quantity of data required make this methodology applicable to a limited number of cases.

Preference should thus be given to a step-by-step approach which discriminates the fans with a high level of hazard (requiring comprehensive modelling) from those where simplified modelling might be justified. The alternative approach proposed in this study is a volumetric method, which does not need very sophisticated data and takes into account the actual topographic surface and slope gradient. However, crucial to this approach is an adequate estimation of the magnitude of the expected event.

Finally, due to its reliability, the hydraulic method was used to perform a forward modeling of event scenario for similar events in the current topographic setting, as modified by the 2000 event.

Key words: Debris flow, spatial hazard assessment methods, back analysis, forward modelling, Italian western Alps

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INTRODUCTION

In the period 13-16 October 2000, a severe weather disturbance affected a wide portion of north-western Italy, involving in particular the high Po river valley (Piemonte and Valle d'Aosta regions). The related intense rainfalls in the wide affected area reached values up to 700 mm of cumulated rain during the event with peaks of rainfall intensity on the order of 50 mm/h. As a consequence, several and significant floods and slope instabilities were triggered and caused many damages on the infrastructures as well as on the human settlements, with a final toll of 25 fatalities.

The slope phenomena that occurred were prevalently of the debris-flow (Pierson and Costa, 1987) and debris-flood type, related to the interaction of liquid and solid discharge fed by catchment basins. Such basins are featured by narrow and deeply incised valleys, high topographic gradients and thick debris covers.

This paper focuses on the debris-flow event that affected a wide portion of the municipal territory of Nus (Valle d'Aosta region, Northern Italy), located in the catchment area of the St. Barthélemy river - a left

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tributary of the Dora Baltea river - as well as the alluvial fan on which the town rises (Fig. 1).

The aim of the present study was to compare different methods for mapping and/or simulating the extent of areas potentially invaded by debris-flow events on alluvial fans such as the one under study, also to test their possible applications to similar Alpine alluvial fans. The suitable methods range from geomorphological (Costa, 1984; Jackson et al., 1987), to geotechnical (Fleming et al., 1989; Johnson, 1984) and dynamic (Hungr, 1995) to strictly hydraulic ones (O'Brien et al., 1993). In this paper the Aulitzky (1980) and Takahashi (1991) methods and a volumetric approach as proposed by Iverson and Schilling (1998) were applied and their results compared. The considered event was also reconstructed via the numerical FDM based commercial software FLO-2D (O'Brien, 2001), whose results were compared with the ones previously obtained.

Fig. 1- Aerial photograph of the study area taken immediately after the October 2000 event: the main effects of the debris-flow, especially in terms of depositional areas, are clearly visible.

Finally, the results of each method were compared with the actual effects of the 2000 event in order to assess their reliability.

DESCRIPTION OF THE EVENT

In the Valle d'Aosta region, the rainfall events of October 2000 affected mainly the right tributaries of the Dora Baltea river valley, where peaks of 600 mm of cumulated rain were reached over a period of 80 hours. Anyhow, significant rains (on the order of 200 mm in the same time interval) occurred also on the left-hand slope of the Dora Baltea river, where the drainage basins that feed the St. Barthélemy river are located. No direct rainfall data are available for the study area; these data where then inferred from the meteorological station of St. Christophe, located about 10 km west of the town of Nus. This station lies in the same main valley (Dora Baltea river) at an altitude close to the one of the urbanised area of the municipality.

Figure 2 shows the pattern of rainfall in 1-hour intervals as well as of accumulated rainfall. The entire event lasted 85 h; rainfall totalled 257.8 mm. The 24-h period with the highest rainfall (146.6 mm) was the one elapsing from 6:00 pm of 14 Oct. 2000 to 5:00 pm of 15 Oct. 2000. The maximum hourly intensity of rainfall was not particularly relevant, as it reached a maximum of 10 mm/h.

In this period, a particularly significant slope instability occurred in the municipality of Nus, where a huge quantity of debris material was mobilised, feeding solid transport in rivers (Fig. 1). Significant quantities of alluvial and vegetal material were transported by rivers. In particular, the St. Barthélemy river acted as a chute which collected a large amount of water and debris; the latter was fed by both landslides at the higher part of the

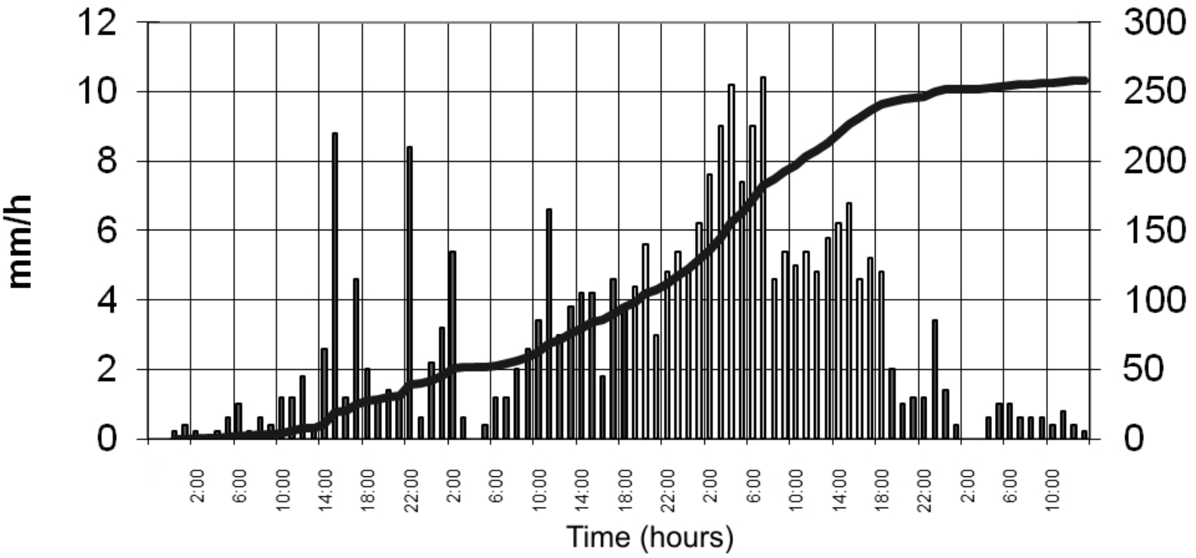

Fig. 2 - Rain graph for the event of 2000 in the time interval from 10/13/2000 at 00.00 a.m. to 10/16/2000 at 1 p.m.. The histogram bars refer to the rain intensity (the light grey ones indicate the most intense rainfall period), while the black line indicates the cumulative rain.

basin and colluvial cover along the path. Due to the narrow shape as well as to the steepness of the valley, the flow reached high velocity and energy, as testified by the intense erosion of the colluvial cover along the path as well as by large-sized transported boulders, width of the invaded area and the incision of a new diversion channel.

MAPPING OF THE EVENT

The material carried by the St. Barthélemy river, reached the apex of the fan where the town of Nus is settled. The main effects of the debris-flow/flood were surveyed and mapped (Fig. 3). In this zone, near a bridge over the river, the flow generated a deposit which resulted into obstruction of the original bed. Accumulation of the debris, which included blocks and boulders with volumes up to 15 m^3, diverted the course of the river, causing overflow. Samples of the debris were collected immediately after the event in different locations over the debris fan; the grain size distributions of some significant samples are reported in figure 4.

Water runoff divided into two branches: the left one flooded most of the populated area, while the right one flowed towards the valley, leaving the old stream bed and depositing a significant quantity of debris. The original stream bed is now completely obstructed and deserted.

Most of the surface of the fan was invaded by water and the debris flow (Fig. 3). The alignment of the stream bed moved westwards, running at the foot of the slope where the town of Mazod is located. In this area lies an about 600 m long and 10-15 m high erosional slope, caused by the flood. The morphometric data for the fan and the basin are summarised in table 1.

The quantity of debris that reached the fan was estimated at first through empirical formulas. For estimation purposes, some relations using geological and geomorphological parameters and various coefficients (steepness, average slope, local lithotypes, etc.) were compared; the results are as follows:

Bottino et al. (1996)
M = 21241•A 0.28 [1] 72,587 m^3
Rickenmann and Zimmermann (1993)
M = (110-2.5•S)•L [2] 87,352 m^3
Hampel (1977)
M = 150 A•(S-3)2.3 [3] 240,353 m^3

Where A is the surface of the catchment area, S is the slope angle of the alluvial fan and L is the length of the stream.

All the mentioned volume estimates gave highly uneven results and only provided a rough indication of the quantity of mobilised debris that might reach the fan upon extreme phenomena. The actual event was greatly underestimated, as the intersection of two digital models (as it will be explained in more detail afterwards) yielded a volume of 636,000 m^3.

Fig. 3 - Schematic map showing the main effects of the debris-flow surveyed after the event. Key to legend: a) Location of the main obstruction point where the flow diverted into two main branches; b) Heavily flooded area with deposition of coarse grained debris (boulders and gravel), locally incised by transportation channels; c) Boundary of the sector dissected by channels; d) Migration direction of the main channel; e) erosional scarp; f) Heavily flooded area with deposition of sandy debris; g) Lightly flooded area with deposition of sandy and silty debris.

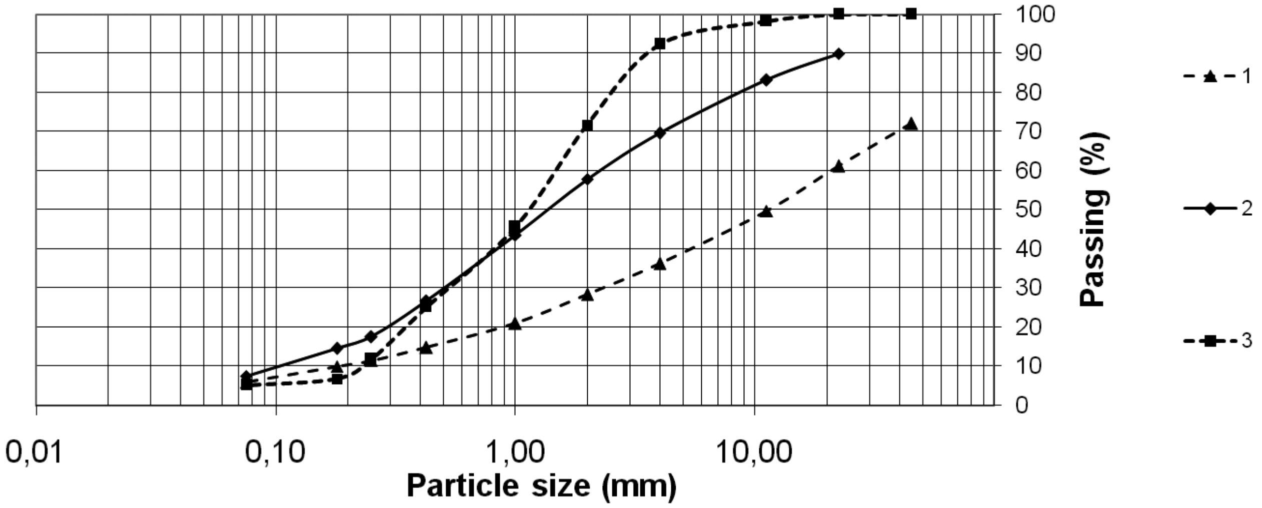

Fig. 4 - Grain size distributions of some samples of debris collected in various parts of the fan after the event (1- apex of the cone; 2- middle part; 3- distal part).

SPATIAL HAZARD MAPPING AND RUN-OUT BACK ANALYSES USING DIFFERENT METHODS

Geomorphological method

Aulitzky's method (1980) is a technique used for spatial hazard mapping and classification of potential disastrous events stemming from mountain torrents, avalanches, and floods. The method is based on morphological and morphometric observations made directly in the field. In particular, this method allows to assign each observation point a value of hazard, based on a rating derived from a specific questionnaire (questions 1-6 of the original method, concerning the features of the deposit, the inclination of the debris cone fan, the morphology and vegetation cover of the surface, the discharge situation on the debris cone) (Tab. 2). Four answers, corresponding to values from 1 to 4, are available for each question. For each observation point it is possible to obtain a mean value by dividing the overall rating (sum of the ratings of the answered questions) by the number of answered questions. The so obtained value expresses the hazard level of the observation point if compared with predetermined threshold values (> 2.6; < 2.6 and > 1.6; < 1.6; corresponding to high, moderate and low hazard, respectively). In this paper we applied a modification of the Aulitzky's method proposed by Ceriani et al. (1998) and calibrated for the debris-flow fans of the Italian Alpine chain. The method by Ceriani et al. (1998) has been widely adopted for several case histories in Italy mainly for land-use planning and management purposes (see for example Tomasetti et al., 2004). It differentiates from the original method for the extension of question 6, where the discharge condition of both channel and debris cone area are taken into account.

ALLUVIAL FAN	
Total area	0.9 km^2
Average fan slope	6.6%
Maximum altitude	580.00 asl
Minimum altitude	520.00 asl
Length of drainage basin	936 m
BASIN	
Area	80.5 km^2
Maximum elevation	3,490 m asl
Minimum elevation	580 m asl
Average slope of main drainage basin	20.3 %
Mean elevation	1,303 m
Perimeter	44,487 m
Length of hydrographic network	273,394 m
Drainage density	3,394
Form factor	14.130
Melton Index	0.323

Tab. 1 - Morphometric data of the study area.

In order to apply this methodology, the survey of the fan area was based on 1:10,000 scale maps. The fan area was divided into 50x50 m square cells. Each cell was assigned a number and all the questions included in the questionnaire associated with the method were addressed for each cell; scores were assigned and the relative averages were calculated on the basis of the survey.

The thresholds used for the moderate and low risk classes were 2.6 and 1.6, respectively. The results are shown in figure 5.

Takahashi's approach

Based on available reports, the path of a debris flow

Question 1	**Maximum grain volume of recently eroded material**	**Points**
	a) 1 m^3 and more	4
	b) 0.2 to 1.0 m^3	3
	c) 0.01 to 0.2 m^3	2
	d) Less than 0.01 m^3	1
Question 2	**Maximum thickness of single debris layers that can be differentiated by the soil horizons or the textural breaks**	**Points**
	a) 1 m and more	4
	b) 0.5 to 1.0 m	3
	c) 0.1 to 0.5 m	2
	d) Smaller than 0.1 m	1
Question 3	**Inclination (gradient) of the debris cone domain under study**	**Points**
	a) More than 15%	4
	b) 7 to 15%	3
	c) 2 to 7%	2
	d) Less than 2%	1
Question 4	**The present vegetation cover is**	**Points**
	a) pioneer vegetation of alnus, salix, myricaria on stony terrain to patches with first succession of larch, pine and spruce	4
	b) advanced succession of even aged larch, birch, pine and spruce stands on coarse gravelly terrain	3
	c) characterized by the predominance of meadows and pasture broken by stone fences and stony soils	2
	d) characterized by fields without stone fences or terraces and only minor stony materia1 in the soil	1
Question 5	**Are the erosional features and surface irregularities on the debris cone domain**	**Points**
	a) debris ridges and erosional furrows with coarse blocks, that can be identified as domains with concentrated high-velocity debris flows	4
	b) poorly defined depositional features created by spreading debris flow or by its redeposition	3
	c) elevated surfaces along the incised torrent which could only be affected by a blockage of the channel	2
	d) distinctly elevated surfaces above the incised torrent channel. that cannot be reached by debris from the channel, but lo which access could be interrupted?	1
Question 6	**The discharge situation on the debris cone is**	**Points**
	a) characterized by the presence of blocking structures above the domain of interest (e.g. bridges, culverts of small diameter, narrows, dams etc.) or other structures that inhibit the free discharge above, laterally or below the point of reference (flat reaches with less the 3% gradient, sharp bends, restrictions along the receiving river) which would force channel abandonment even with a minor debris load	4
	b) similar situation as at (a) except that only broken logs and very coarse boulders would force channel abandonment	3
	c) characterized by absence of significant obstacles but only moderately incised flat channel and a relatively free debris discharge potential of the receiving river	2
	d) channel works on the lower course which could easily handle the design load	1

Tab. 2 - Questionnaire related to the first step of the original Aulitky's method.

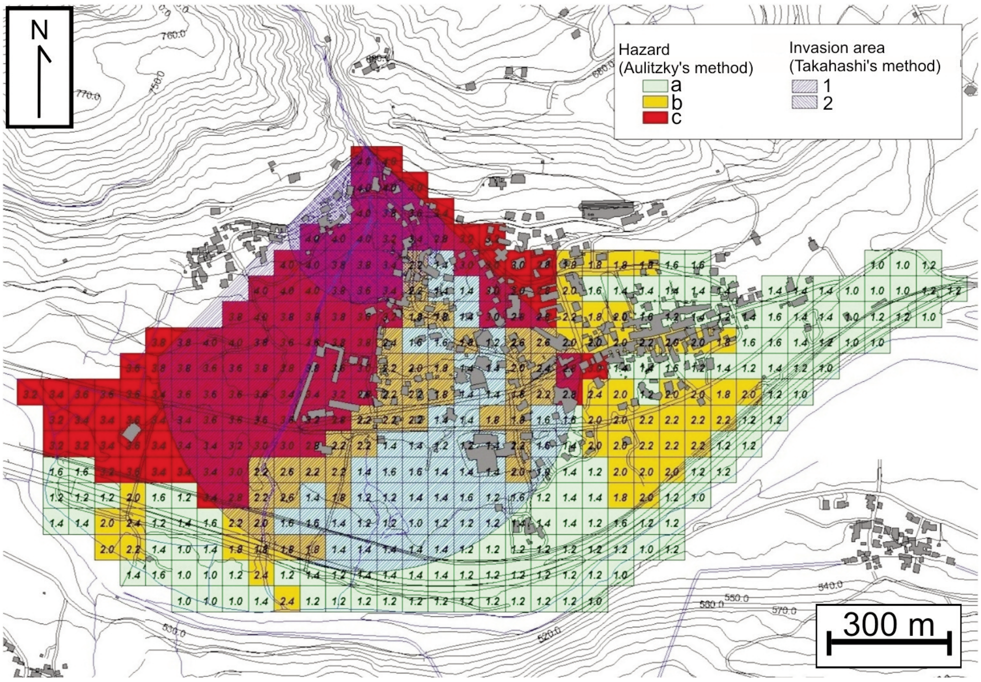

Fig. 5 - Map showing the spatial hazard zoning using Aulitzky's modified method and the envelope of the invaded area according to Takahashi's method, for two volumetric concentration assumptions. Key to legend: a) < 1.6 (low); b) 1.6÷2.6 (medium); c) > 2.6 (high); 1) volumetric concentration 0.15; 2) volumetric concentration 0.2.

and the area potentially subject to deposition can be estimated. This may be done by using Takahashi's theoretical-empirical model (1991), based on experimentally investigated modalities whereby a debris flow stops after a sharp reduction in slope.

The distance x_L within which the debris flow stops is written as

$$x_L = \frac{U_0^{\,2}}{G} \qquad [4]$$

where

$$U_0 = U\cos(\theta - \theta_0)\cdot\left\{1 + \frac{\left[\left(\rho_s - \rho_f\right)\cdot \nu_D k_a + \rho_f\right]\cdot \cos\theta \cdot gD}{2\cdot\left[\left(\rho_s - \rho_f\right)\cdot \nu_D + \rho_f\right]\cdot U}\right\} \quad [5]$$

$$G = \frac{\left(\rho_s - \rho_f\right) g \nu_D \cos\vartheta_0 \tan\Phi_D}{\left(\rho_s - \rho_f\right)\nu_D + \rho_f} - g\sin\vartheta_0 \qquad [6]$$

The parameters to be estimated are: velocity U, thickness D, volumetric concentration ν_D and dynamic friction angle of the mixture Φ_D; q and θ_o are the slope gradients respectively of the upslope zone and of the depositional zone of the debris flow and k_a is a coefficient quantifying the action of active soil pressure with changes in slope.

Debris flow velocity was estimated by using two empirical relations, the first proposed by Takahashi (1991) and the second suggested specifically for mud flows by Syanozhetsky et al. (1973). The values of the parameters are listed in table 3.

This type of analysis is considerably affected by variations in volumetric concentration (ν_D) and in dynamic shear strength (Φ_D), as highlighted in the graph of figure 6; the graph shows the trend of the maximum depositional distance function, which depends on volumetric concentration and dynamic shear strength.

As stated by Takahashi (1991), the analysis above assumes that a quasi-steady debris flow having a forefront is supplied from upstream. In a real event the discharge decreases with time.

Parameter	value
C	3
θ	10°
θ_o	6°
ka	0.33
Φ_D	25° and 35°
D	5 m
ρ_s	27.5 kN/m³
ρ_f	10.0 kN/m³
ν_D	0.25 and 0.15
U	10 m/s

Tab. 3 - Values of parameters using the methodology proposed by Takahashi.

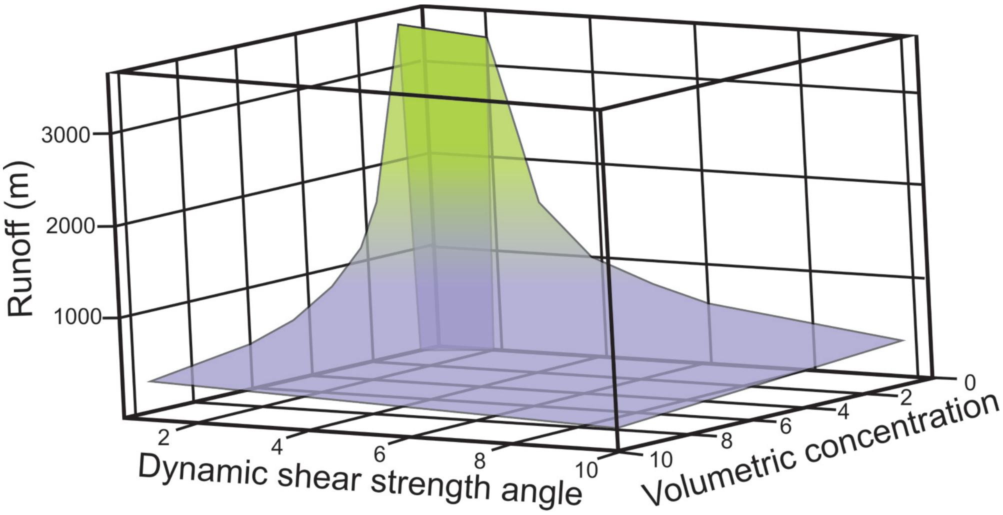

Fig. 6 - Graph showing the variation in the debris flow depositional distance as a function of ν_D and Φ_D.

In this study two types of data processing were compared, all other conditions being equal: the first using a value of volumetric concentration of the mixture of 0.20 and the second one of 0.15, both values being plausible for the event that occurred in the past. The results obtained are shown in figure 5; the maximum depositional distances are 305 and 824 m, respectively; the areas invaded by the debris flow are contoured.

Volumetric Method

An assessment of potentially flooded areas was performed by adopting the procedure proposed by Schilling (1998) and Iverson (1997) and Iverson et al. (1998). Such a procedure has been partially modified, as its original form is addressed to zones vulnerable to lahar flooding.

The method is founded on the following assumptions: I) flooded zone B is proportional to the magnitude of the event; II) the cross-section A along the path remains constant.

The authors developed the following semi-empirical equations in order to derive the above quantities:

$$A = c \cdot V^k \quad [7]$$

$$B = d \cdot V^k \quad [8]$$

where V is the flow volume. The coefficients (c and d) and exponents (k) derive from a statistical analysis carried out on 27 lahars, and, the authors themselves explain, the above coefficients must be corrected for different phenomena.

In this case study, the values of volume derive from the calculated volume balance in section 4.4, while the coefficients and exponents derive from the statistical analysis on forty debris flow basins in the Italian Alps by Berti and Simoni 2007 (Tab. 4).

A software programme was developed to determine the areas potentially subject to flooding. Starting from parameters such as digital terrain model and water flow line, the software calculates the envelope of the flood area. The software, which runs in an ArcView environment, uses the related "Avenue" programming language and its many spatial calculation and primitive graphics functions (Razay and Warwick, 1997). The algorithm derived to determine the flood area proceeds in steps along the river bed, determining the flood section area in a direction perpendicular to the flow. The shape of the flood area is determined by increasing the water level at each step with respect to the flow line, finding the intersection of this level with the digital terrain model. This iterative process is stopped when the value of the *a priori* assumed hydraulic section fits with the calculated one. The envelope of the intersections found at each step, between the water level and the digital model (on the left and right sides of the water flow direction) defines the flood area. Even if this method (Fig. 7) should be applied only for a confined flow, previous experiences (Berti and Simoni, 2007) testify for its suitability as a tool for providing a rough estimation of partially unconfined flooding scenarios.

This computational sequence is very similar to the procedure proposed by Schilling (1998), the main differences lying in the automatic cross-section extraction.

Parameter	Value
V	636000
c	0.1
d	100
k	0.66

Tab. 4 - Values of parameters using the methodology proposed by Iverson and Shilling.

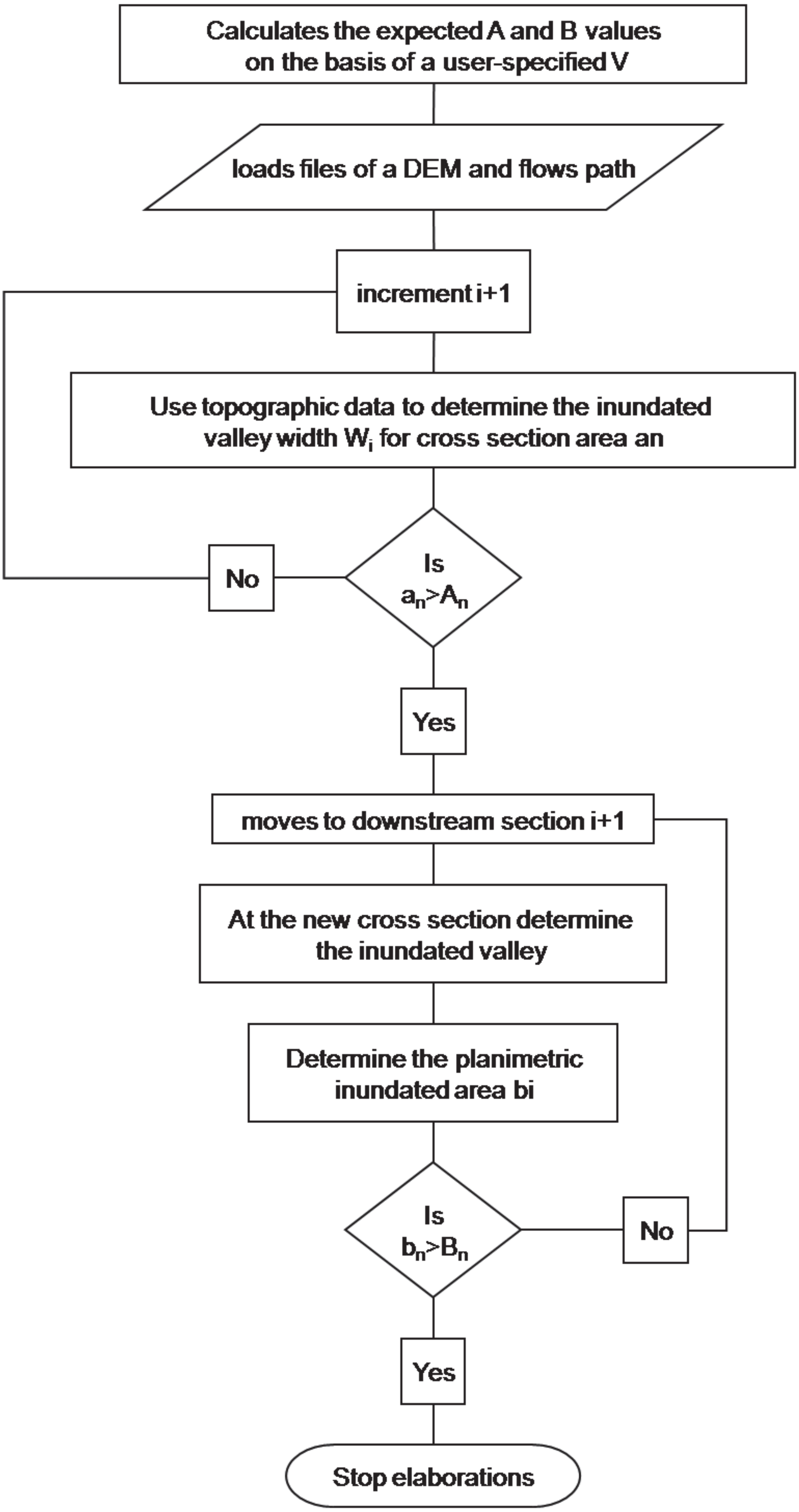

Fig. 7 - Flow chart showing the procedure of the volumetric method.

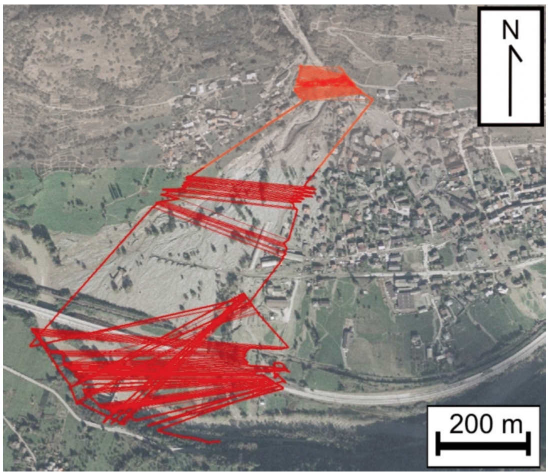

Fig. 8 - Mapping of invaded areas using the proposed volumetric method. The red lines show the envelope of the flooded areas. Background: aerial photograph of the past event.

The input parameters of the software are: number of cross sections, maximum length of the section, increase of water level with respect to the flow line and surface area of the assumed section as a function of the estimated flow rate.

Varying the input parameters enables to compute flood areas for a wide array of situations and to estimate the potentially flooded areas. The availability of a fairly accurate digital terrain model, with a closely-meshed grid is very important for this type of analysis. This allows the computational algorithm to converge in the iterative process of searching for envelope points of the flood area. Indeed, the parameter relative to the maximum length of the section was introduced with the purpose of stopping the iterative process when no convergence is attained. figure 8 shows the result of the simulation.

Hydraulic Method

Hydraulic method uses continuity and motion equations. In order to simulate the behaviour of the debris flow, a commercial software programme called FLO-2D™ (O'Brien, 2001) was used. This is a completely dynamic 2D finite-difference hydraulic software programme that can also treat fluids other than water; the software considers these fluids as single-phase compounds in which various physical processes interact to define their rheological behaviour. The software uses a quadratic shearing stress model, which can describe the energy exchange processes occurring among the particles of viscous fluids.

Input data required for the simulation are the hydrograph of the event, the value of the solid concentration of the mixture and the total flow. As regards the first aspect, the starting point was the rainfall data from the meteorological station of St. Christophe, located about 10 km west of the town of Nus (see section 2).

The hydrograph (Fig. 9) was derived from rainfall using Nash's procedure (1960).

The conversion rainfall-runout is represented conceptually by a series of n identical linear reservoirs

$$h(t) = \frac{1}{k}\left(\frac{t}{k}\right)^{n-1} \cdot \frac{e^{-\frac{t}{k}}}{\Gamma(n)} \qquad [9]$$

where h(t) is the discharge per unit area at time t, k is the coefficient of storage of each linear reservoir, and Γ(n) is the standard gamma function:

$$\Gamma(n) = \int_0^\infty m^{n-1} e^{-m} dm \qquad [10]$$

where m is an integration (or dummy) variable. The corresponding hydrograph for the series of n identical

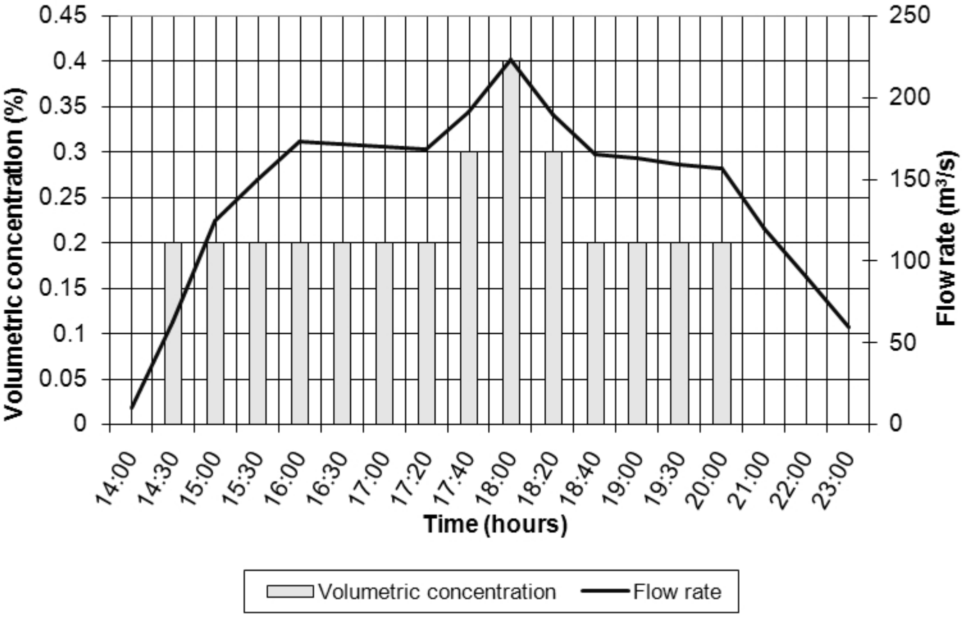

Fig. 9 - Reconstruction of the hydrograph with related volumetric concentration.

linear reservoirs is found by integrating

$$g(t) = \int h(\tau)d\tau \qquad [11]$$

With regard to the other required input parameter, i.e. the value of volumetric concentration, the following information were required:

- pattern of the event;
- mass balance obtained by assessing the quantity of transported material.
- maximum volumetric concentration;

Firstly, a triangular pattern was assumed (as reported for similar cases); this assumption was confirmed by the reconstruction of the event on the basis of eye-witness accounts and audiovisual reports.

For the mass balance, assessments were carried out on the basis of the determination of the material mobilised during the investigated event. Two digital terrain models (1:10000 scale) - the first built in 1991 and the second a few days after the event and covering most of the affected areas - were intersected.

The results are displayed in figure 10. In short, it can be stated that the volume transported in the most affected western area was as low as 477,000 m^3, while for the whole fan the volume was calculated to be equal to 636,000 m^3. The intersection of the two digital models made it possible to study in detail how the material was mobilised. In particular, most of the volume was mobilised in the final portion of the river bed before flowing into the fan.

The maximum volumetric concentration was obtained by applying Takahashi's theory (1991). In particular, it was necessary to assess the maximum volumetric concentration upon triggering of the event, which was done on the basis of the geotechnical characteristics of the debris (Lebourg et al., 2003). The Takahashi's relation defines the volume concentration of the solid in the fluid in the following form:

$$c = \frac{\rho \cdot \tan\vartheta}{(\sigma - \rho)\cdot(\tan\phi - \tan\vartheta)} \qquad [12]$$

where:
σ = density of the particle
ρ = density of fluid
φ = internal friction angle
θ = slope angle of the of the channel.

These values were determined by laboratory tests and surveys in the area of origin of the phenomenon. Figure 11 shows that the value of volumetric concentration is significantly affected by the slope of the source area. Finally, the total flow Q of the debris-flow (Fig. 12) was determined by correcting the hydrograph in order to consider also the solid fraction according to Ashida (1976)

$$Q = Q_l \frac{c_\infty}{c_\infty - c} \qquad [13]$$

where
Q_l = water discharge
c = the volume concentration of the solid in the fluid
c_∞ =the volume concentration in static condition

knowing the liquid flow determined through the

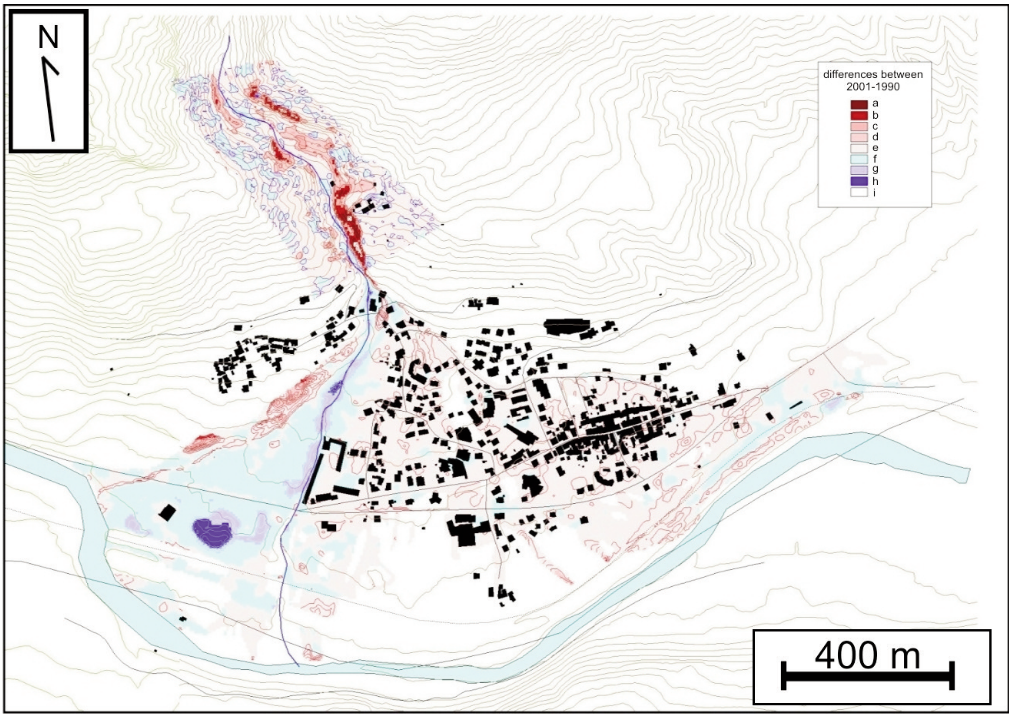

Fig. 10 - Result of the intersection between two DTMs of the investigated area. The differences through which the variations in volume were reconstructed are shown. Key to legend (values in meters): a) -22 ÷ -18; b) -18 ÷ -14; c) -14 ÷ -10; d) -10 ÷ -6; e) -6 ÷ 0; f) 0 ÷ 3; g) 3 ÷ 7; h) 7 ÷ 12; i) no data.

hydrograph and the volumetric concentration on the basis of the previous considerations. This result was obtained by back analysis; the input data for the analysis were not only the above-mentioned data, but also a series of data deriving from geomorphological analyses, such as the effects of the flood, as well as from interviews with eye-witnesses.

In a subsequent step, for calculation purposes the investigated area was subdivided into a grid comprising 9,205 squares measuring 10x10 m, to which values of roughness and elevation above sea level were assigned.

The whole fan from the apex as far as the Dora river was modelled; the modelled area was defined by relying on aerial photos of the event.

The hydraulic model required the definition of the roughness values for the flood area. To do this in univocally, use was made of a technical information plan coupled with the regional maps and providing data on the local vegetal cover. Roughness values are expressed according to Manning's notation. A series of classes were determined on the basis of the soil coding contained in the regional technical map; as it can be seen in the enclosed table 5, the corresponding n values were assigned to the identified classes by using simple conversion tables (COE, -HEC-1 Manual, 1990; COE Technical Engineerig and Design Guide, N. 19, 1997).

In the fan under review, the first two classes prevailed; the values used were validated via site surveys, which also permitted to assess the reliability of the maps used. The roughness values were obtained at the end of a parametric analysis starting from bibliographic data (COE, -HEC-1 Manual, 1990; COE Technical Engineerig and Design Guide, N. 19, 1997).

The rheological law, as proposed by the author of the

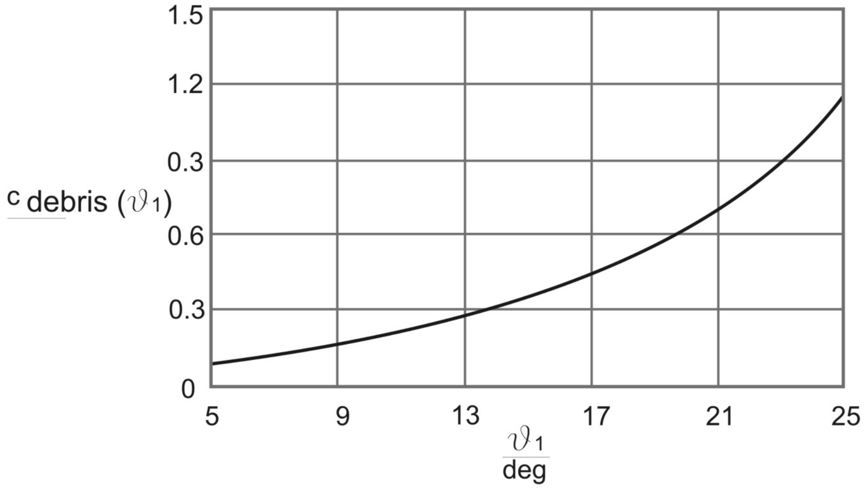

Fig. 11 - Graph showing the dependence of the maximum volumetric concentration on the slope gradient of the source area.

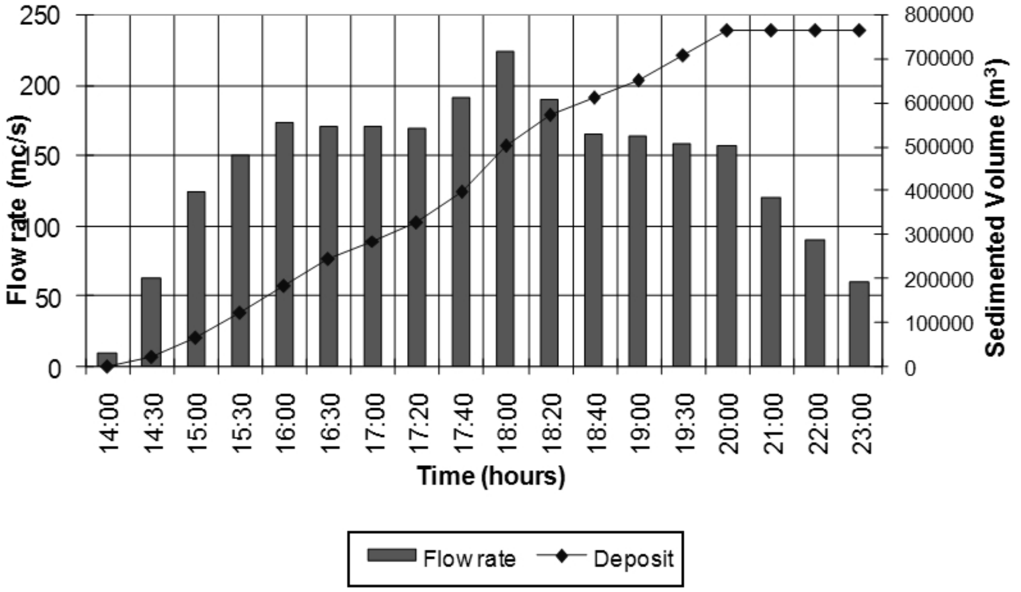

Fig. 12 - Corrected hydrograph with solid and fluid part.

Surface	**n-value**
Asphalt or concrete	0.04
Sparse vegetation	0.10
Poor grass cover on rough surface	0.20
Forest and dense grass, dense vegetation	0.35

Tab. 5 - Overland flow Manning's n roughness values.

software programme, is as follows (O'Brien and Julien, 1985):

$$\tau = \tau_y + \eta\left(\frac{dv}{dy}\right) + C\left(\frac{dv}{dy}\right)^2 \qquad [14]$$

where

$$\tau_y = \tau_c + \tau_{mc} \qquad [15]$$

and

$$C = \rho_m l^2 + f(\rho_m, C_v)\cdot d_s^2 \qquad [16]$$

In these equation h is the dynamic viscosity; τ_c is the cohesive yield strength; the Mohr Coulomb stress $\tau_{mc}=p\tan\varphi$ depends on the intergranular pressure p and the friction angle φ of the material; C denotes the inertial shear stress coefficient, which depends on the mass density of the mixture ρ_m the Prandtl mixing length *l*, the sediment size d_s and a function of the volumetric sediment concentration Cv. Bagnold (1954) defined the function relationship f(ρ_m, Cv) as:

$$f(\rho_m, C_v) = a_i \rho_m \left[\left(\frac{C_*}{C_v}\right)^{\frac{1}{3}} - 1\right] \qquad [17]$$

where ai(≈ 0.01) is an empirical coefficient and C* is the maximum static volume concentration for the sediment particles.

Aspects pertaining to human settlements were taken into account by digitising buildings, roads and, namely, the channel. In particular, the channel element was introduced by defining the 49 surveyed sections in terms of geometry and roughness (whenever possible) and derived from the available maps and images taken prior to the event in areas which were not accessible because they were covered by transported sediments.

As regards the results, the first assessment concerned the maximum flow velocity reached during the paroxysmal stage of the event. The model generated a file showing that maximum velocity values are concentrated in the top part of the fan (Fig. 13a). The velocity values for the flood flow are about 8-10 m/s while, as regards the fan, the flow velocity is much lower, i.e. about 2-3 m/s. The above values agree with reconstruction of the event based on amateur films.

The maximum thickness values of the debris flow were also determined (Fig. 13b). The figure shows that these values were influenced by man-made components on the fan; in particular, the role of roads (especially those located in the direction of maximum slope) in diverting the flow is evident. Railway and motorway embankments had an adverse impact, by limiting runoff towards the Dora river; local culverts were definitely insufficient, even without considering their obstruction by vegetation. The thickness reached by debris was significant near the flood flow, but even in the populated area it reached a maximum of 2-3 m.

Using the Zeller and Fullerton equation (1983), the programme calculates the sediment transport in terms of the flow rate of material per unit length. Actually, this equation was studied in order to assess any solid transportation phenomena; consequently, it does not take into account the presence of floating materials, such as logs, that had significant effects in the investigated case.

In this study, the equation was used only to roughly estimate the capability of the flow to generate erosion or sedimentation.

The equation estimates the inflow or runoff as follows:

$$q_s = 0.0064 \cdot n^{1.77} \cdot V^{4.32} \cdot G^{0.45} \cdot d^{-0.30} \cdot D_{50}^{-0.61} \qquad [18]$$

where
n = Manning's coefficient
V = average flow velocity
G = gradation coefficient
d = flow thickness
D_{50} = diameter of fiftieth percentile of sediment.

The values G and D_{50} derive from the laboratory analyses carried out on the samples of debris collected in the fan. It is worth stressing that - due to the implemented algorithm - this assessment is performed without considering the topographic variations due to erosion and/or deposition, i.e. any deposition or erosion does not affect the flow assessment at each time step.

Obviously, the most affected areas were those lying near and among buildings, which acted as obstacles to the flow and influenced the outflow from the fan. The last data processing stage was focused on erosion and sedimentation, which were assessed by means of the above-mentioned equation. The most affected areas were those to the west, where the depth of erosion reached 10 m and the maximum deposit thickness reached 6 m.

DISCUSSION

This section focuses on the reliability of the spatial hazard mapping and back-analyses by comparing the results of each method with the map of the actual effects shown in figure 3.

The result of Aulitzky's methodology was far from being precautionary; if it had been used predictively, it would have significantly underestimated the actual

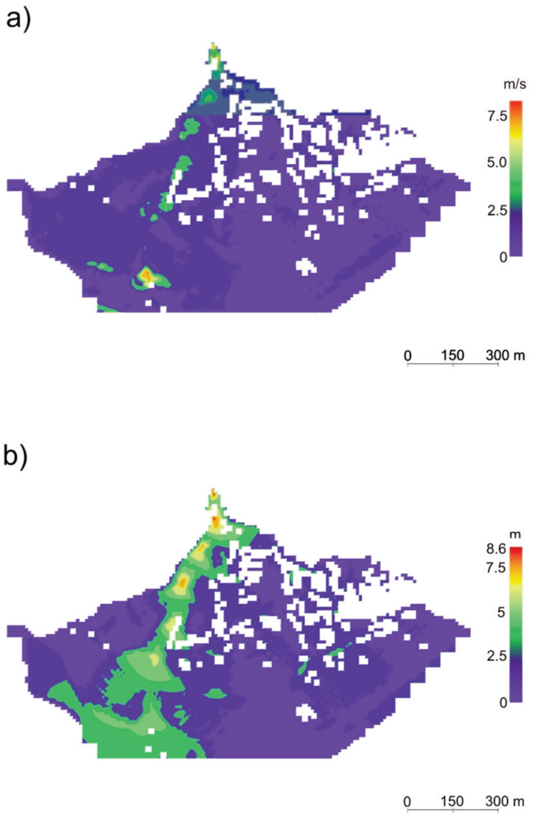

Fig. 13 - Flow velocity (a) and thickness (b) for the past event, determined via FLO2D. The white cells indicate the areas occupied by structures and excluded from data processing.

“magnitude” of the 2000 event. Indeed, vast zones that would have been classified as low hazard ones were actually affected by debris flows of even considerable thickness.

In general terms, during this study it was possible to point out a main critical issue in applying the Aulitzky’s methodology (both the original and the modified one): if a simple arithmetic mean of the ratings of the six questions is adopted for each cell, significant under- or overestimations of the actual hazard conditions can be generated due to possible scatter of the values related to each question. This observation suggests firstly to consider the standard deviation with the purpose of accounting for the scatter of the data. In addition, reliance was made on the harmonic mean rather than on the arithmetic mean, as the former provides the truest average especially when rates and ratios are involved (Yalun, 1975). For example, the harmonic mean is used in hydrology to average hydraulic conductivity values for flow that is perpendicular to layers (Seong, 2002).

For this purpose, reliance was made on the following Harmonic Mean function (Murray, 1983):

$$HM = \frac{N}{\frac{1}{x_1} + \frac{1}{x_2} + \cdots + \frac{1}{x_n}} \qquad [19]$$

Based on the above mentioned observations, in this study a further modification of the Aulitzky’s methodology was attempted: a first filter for the assessment of the hazard conditions can be adopted on the basis of the harmonic mean value and the related standard deviation. If the Harmonic Mean + standard deviation is < 2, no high hazard exists; if the Harmonic Mean - standard deviation is > 2, no low hazard exists. Furthermore, if these conditions are not encountered, a dynamic threshold can be adopted in order to account for the actual distribution and variability of the parameters involved in the classification. In this case it is possible to make a preliminary discrimination on the basis of the resulting from the sum of ratings associated with questions 7 - 11 of the original Aulitzky’s method, that account for the overall conditions of the fan. If the value of 15 is considered as a discriminating factor of the overall conditions of the fan, new dynamic thresholds can be then set as shown in table 6.

The so defined thresholds appear to better account for the actual calamitous event that occurred; the above-mentioned thresholds are undoubtedly more adequate to describe the hazard level of the area (Fig. 14). This approach could permit to obtain a more conservative classification if the presence of high hazardous fans and significant data scatters (due to either uncertainty or ambiguous information) is considered.

As regards the Takahashi’s approach, the main issue is related to the strong dependence of the results on the volumetric concentration (ν_D) and the dynamic shear strength (Φ_D) values. For example, an although small increase in volumetric concentration implies a large variation in the extent of the invaded area, which ranges from 72 to 533 ha. The high sensitivity to this parameter implies the necessity to achieve an extremely accurate estimation of volumetric concentration in order to have accurate predictions of invaded areas.

The results of the Volumetric approach show a significant convergence in identifying the actually invaded area in the western sector near the river bed. However, the simulation convergence is not entirely satisfactory in the central area of the fan, which has a zone posing problems of convergence to the software programme. Obviously, situations where the flow forks out into two or more branches cannot be taken into consideration.

The need arises for conducting a statistical analysis on a consistent set of data in the area affected by landslides, in order to assess the applicability of the method to other similar cases and to improve the parameters evaluation for a more reliable simulation (Berti and Simoni, 2007).

Finally, the hydraulic method was validated by comparing the transported volumes estimated by crossing the two digital models (pre- and post-event) with those inferred from processing of the model. Differences fall in the 30% range, a result considered to be acceptable in simulating events of this type. Files regarding the reliability of the simulation, were checked

ASSUMPTION	HAZARD	DEFINITION	VALUE
Sum 7-11 <15	Low	< HM	<1.85
	Moderate	>HM and <HM+ st dev	>1.85 and <2.79
	High	>HM+ st dev	>2.79
Sum 7-11 >15	Low	<HM – st dev /2	<1.38
	Moderate	>HM – st dev /2 and <HM + st dev /2	>1.38 and <2.32
	High	>HM + st dev /2	>2.32

Tab. 6 - Conditions used to define the spatial hazard level using Aulitzky's method as modified in this study.

for consistency with the imposed conditions. In the case under review, variations were not too significant and found in a limited number of grid points. The flow was generally subcritical; only in some parts of the channel and for a limited period of time it became supercritical. This result agrees with outcomes from previous studies carried out by Armanini (1999) in artificial channels. The conservation of mass was guaranteed, as the maximum variation is on the order of 0.01%.

FORWARD MODELLING OF EVENT SCENARIOS AND ZONING PROPOSAL

Once back analysis was completed, the programme was run to answer the following questions: whether a phenomenon similar to the one occurred in the past might occur again and which consequences it might have in the current situation. "Current situation" obviously means the one corresponding to the latest topographic survey used for reconstruction of the digital model required for data processing; the model was built in April 2001.

All the relevant data, especially those on buildings, roads and drainage works were updated. Data on velocity, thicknesses, erosion and sedimentation material were processed; the results, used for the risk zoning proposal (see next paragraph), are not presented individually. The assumed event scenario is markedly

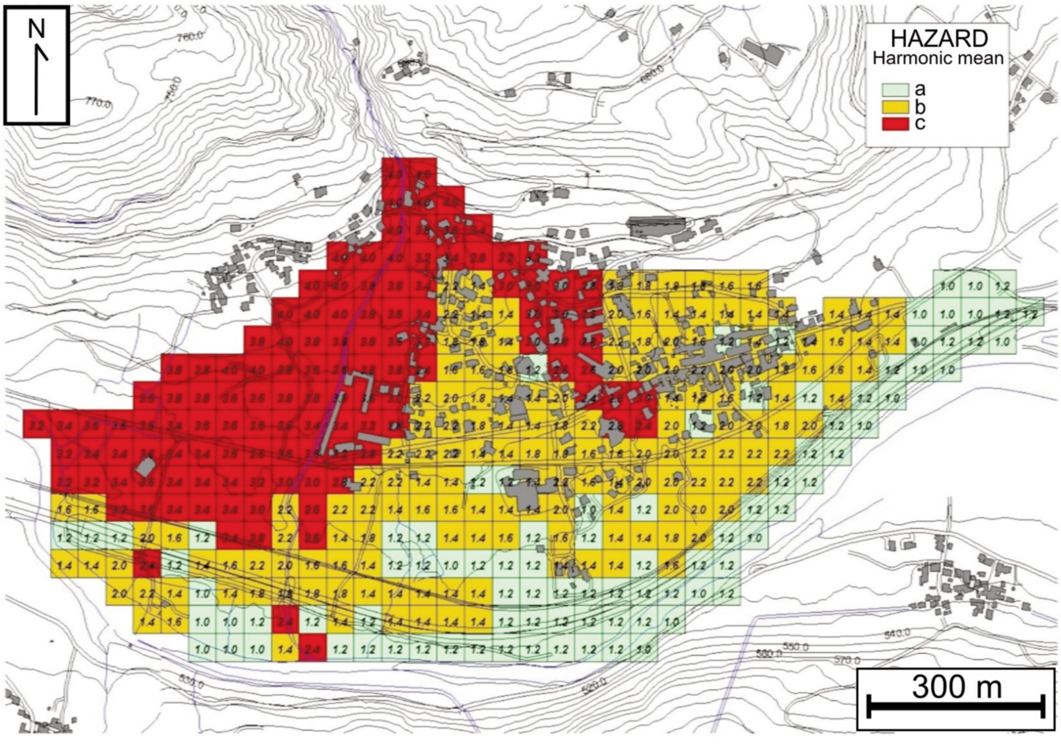

Fig. 14 - Spatial hazard map obtained by using Aulitzky's methodology and the thresholds proposed in this study according to the harmonic mean. Key to legend: a) < 1.38 (low); b) 1.38÷2.32 (medium); c) > 2.32 (high).

HAZARD	**Velocity (m/s)**	**Thickness (m)**	**Erosion/ Sedimentation (m)**
High	> 2.0 or	> 1.0	
Moderate	≤ 2.0 and	≤ 1.0	
Low	< 1.0 and	< 0.5 and	< 0.5

Tab. 7 - Conditions used for hazard assessment in this study.

different from the past one. The presence of the newly-formed channel considerably reduces flood areas with respect to the previous case, as almost all the flow would be directed into the channel, which in turn would direct it definitely westwards.

Only during the paroxysmal stage and for a very short time would the flow leave the stream bed and invade a rather small portion of the inhabited area; consequences would be very reduced and would be even more so if a hundred metres or so of embankments were constructed and the current state road flyover crossing the Saint Barthélemy stream were widened.

The above-discussed stages of the study permitted to reconstruct the past event with sufficient reliability and to make some predictions on the basis of the most important parameters characterising the flow, i.e. thickness, and velocity.

In order to propose a methodology applicable to the definition of debris-flow risk areas, according to Hungr (1995), the following table 7 is proposed.

The criteria underlying the methodology are described hereafter.

First, the low hazard zone (where all the conditions shown in the table must be fulfilled) is determined; in this zone, a possible flood might at most create some inconveniences. Then, the high hazard zone is highlighted. If only one of the above indicators is exceeded, then the zone is assigned to the relative hazard class; in this zone, the probability of permanent structural damages or injuries to people is significant. The intermediate class is thus unequivocally determined by exclusion of the other two; although in this zone the risk is lower than in the previous one, it may become significant in the event of particularly adverse morphology or human settlements.

The latter was compared with the results of the geomorphological analyses contained in the study of the flood area carried out after the event, realized by technicians of Valle D'Aosta Geological Survey (Gianotti and Notarpietro, 2001).

A fairly good agreement of the results may be noted (higher than 80% in areal terms), as the zones indicated in the study as the "most flooded sectors" correspond to the high hazard zones, the zones indicated as "sectors crossed by lower energy water" correspond to moderate hazard zones and the remaining areas "affected by local and/or modest flood phenomena" are included in the low hazard zones (Fig. 15).

The results of back analysis were used to develop a hypothetical pre-event risk map; the situation is completely different as regards the current event scenario, in which the extent of the high and medium hazard zones is approximately one third of the earlier one, owing to the fact that the morphology of the water stream has radically changed (Fig. 16).

CONCLUSIONS

Basic for the reconstruction of the October 2000 event in Nus, was the quantification of both meteoric influxes and deposited volume. With reference to meteoric influxes, it was possible to reconstruct the hydrograph for the studied event according to the Nash model (Fig. 9), on the basis of the data derived from the nearby pluviometric survey station of St. Cristophe, which recorded a cumulated rainfall of about 200 mm over a period of about 84 hours. As regards the deposited volume, the value of 636,000 m^3 was calculated by comparing two digital elevation models of the area referred to pre- and post- event topography respectively.

A first attempt of back analyzing the hazard conditions in the debris fan area was carried out by applying the Aulitzky's method (Aulitzky, 1980) partially modified to fit the Northern Italy typical conditions as suggested by Ceriani et al. (1998). The results show a significant underestimation of the hazard related to the October 2000 event, thus suggesting to propose a variation in this methodology such as the adoption of the harmonic mean rather than the algebraic one to better represent the actual situation.

A more accurate assessment and contouring of the invasion area was possible by applying the empirical-theoretical model proposed by Takahashi (Takahashi, 1991), which is based on experimental observations about the behaviour of a flow after a sudden decrease in the slope angle of the stream bed. As highlighted by the results, the most critical aspect of this approach is the strict dependence of the invaded area on the volumetric concentration, which is the most difficult parameter to define.

The potentially invaded areas were also outlined according to the volumetric method (Iverson, 1997; Schilling, 1998; Iverson et al., 1998), which is based on the estimation of the maximum volume of the event. Crucial to this approach is the definition of c, d and k parameters that allow to assess the areal extension of the invaded area as well as of the outflow section.

Finally, use was made of the FLO-2D commercial software (O'Brien, 2001) since it can also simulate fluids different from water. The back analysis of the October 2000 event performed with this software was addressed to calibrate a model aimed to define event scenarios and produce a hazard map. The subsequent zoning of the area was made by adopting velocity and thickness values of the current assessed with this method.

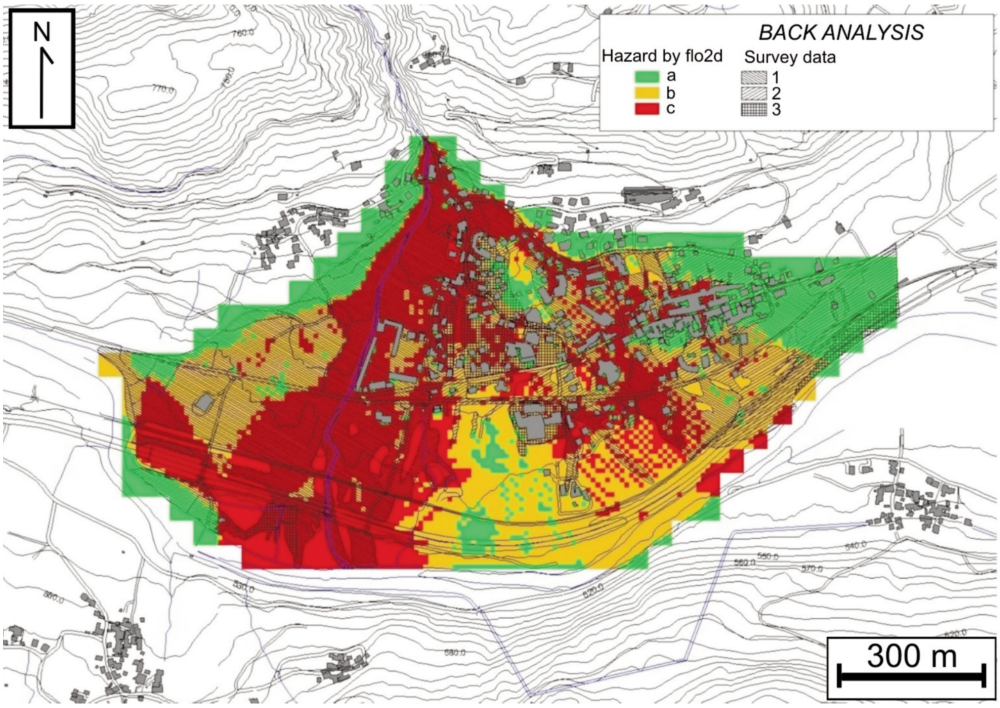

Fig. 15 - Spatial hazard map obtained by back analysis with Flo2D, using the thresholds proposed in this study. Key to legend: a) low; b) medium; c) high; 1) most flooded sector; 2) sector crossed by lower energy water; 3) areas affected by local and/or modest flood phenomena.

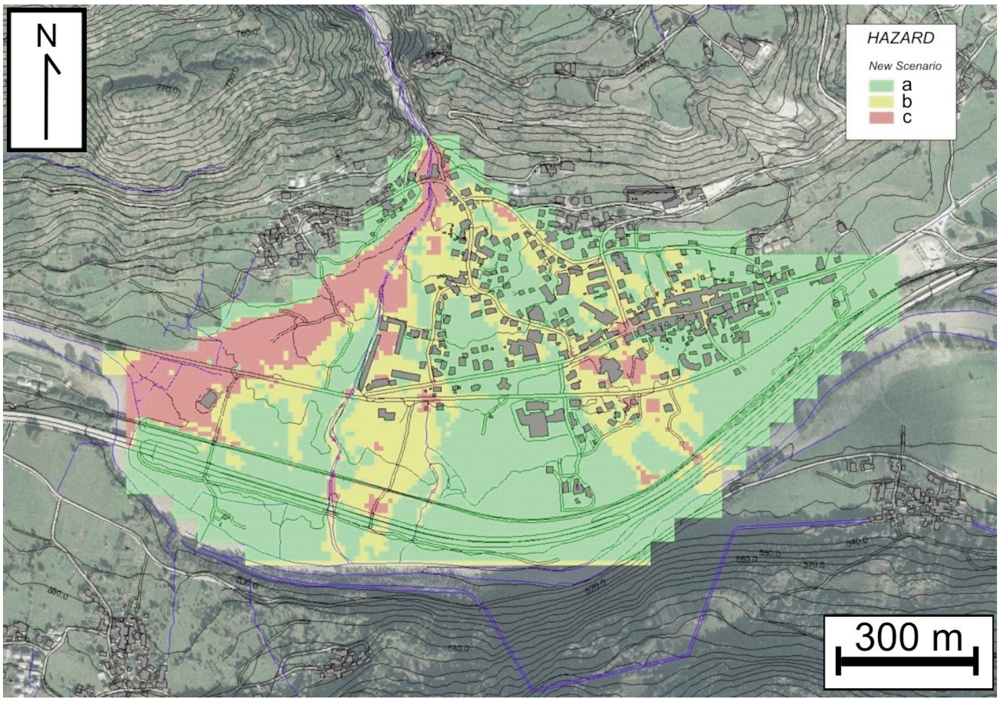

Fig. 16 - Spatial hazard map resulting from the forward modeling of a new scenario using the thresholds proposed in this study. Key to legend: a) low; b) medium; c) high.

Problems in the zoning of alluvial fans affected by debris flows lie in the quality and quantity of data which are required to make event simulation meaningful. Availability of time series, detailed digital terrain models and other hydrological data is scarce. Therefore, hydraulic modelling involving a long processing time can only be applied to a limited number of cases.

Preference should thus be given to an approach that discriminates fans at high hazard, needing comprehensive modelling, from those at low hazard where simplified modelling is justified.

In this regard, reliable results came out from modification of the volumetric method by Iverson et al. (1997) and Berti and Simoni (2007) that does not call for highly sophisticated data and that takes into account the actual topographical surface with obstacles to runoff and actual slope. Nevertheless, adequately estimating the magnitude of the expected event is of crucial importance.

REFERENCES

Armanini A. 1999. Previsione e prevenzione del rischio da colata di detriti. In: Proceedings of Il rischio idrogeologico e la difesa del suolo, Roma, Italy, 01-02 febbraio 1988. Atti del Convegno dei Lincei: 154, 13-44.

Aulitzky H. 1980. Preliminary two-fold Classification of Torrents - International Symposium InterPraevent 1980, Bad Ischl, Austria: 4, 285-309.

Berti M., Simoni A. 2007. Prediction of debris flow inundation areas using empirical mobility relationships. Geomorphology: 90, 144-161.

Bottino G., Crivellari R., Mandrone G. 1996. Eventi pluviometrici critici e dissesti: individuazione delle soglie d'innesco delle colate detritiche nell'anfiteatro morenico di Ivrea. La prevenzione delle catastrofi idrogeologiche: il contributo alla ricerca scientifica: 2, 201-210.

Ceriani M., Fossati D., Quattrini S. 1998. Valutazione della pericolosità geologica sulle conoidi. Professione Geologo: 6, 23-31.

COE 1990. HEC-1 Manual.

COE 1997. Technical Engineering and Design Guide, N. 19.

Costa J.C. 1984. Physical Geomorphology of Debris Flows. In: Costa J.E., Fleisher P.J. (Eds.), Developments and Application of Geomorphology. Springer-Verlag, Berlin Heidelberg, 268- 315.

Costa J.C. 1988. Rheologic, geomorphic and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker V.R., Kochnel P.C., Patton P.C. (Eds.), Flood Geomorphology. John Wiley & Sons, New York, 113-122.

Fleming R.W., Ellen S.D., Algus M.A. 1989. Transformation of dilative and contractive landslides debris into debris flows: An example from Marin County, California. Engineering Geology: 27, 201-223.

Gianotti F., Notarpietro S. 2001. Studio sui fenomeni franosi che hanno interessato il territorio comunale di Nus durante l'evento alluvionale del 15.10.2000 ai fini della definizione della loro pericolosità e dei possibili interventi di sistemazione. Unpublished technical report.

Hampel R. 1977. Geschiebewirtschaft in Widbachen. Wildbach und Lawinenverbau: 41, 3-34.

Hungr O. 1995. A model for the runout analysis of rapid flow slides, debris flows and avalanches. Canadian Geotechnical Journal: 32, 610-623.

Hungr O. 1997. Some methods of landslide hazard intensity mapping. In: Fell R., Cruden D.M. (Eds.), Proceedings of Landslide Risk Workshop. Balkema, Rotterdam, 215-226.

Iverson R.M. 1997. The physics of debris flows. Reviews of Geophysics: 35, 245-296.

Iverson R.M., Schilling S.P., Vallance J.V. 1998. Objective delineation of lahar-hazard zones downstream from volcanoes. Bulletin of Geological Society of America: 110, 972-984.

Jackson L.E., Kostaschuk R.A., MacDonald G.M. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. In Costa, J.E. and Wieczorek, G.F. (eds.), Debris flows/avalanches: process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology: 7, 115-124.

Johnson A.M. 1984. Debris Flows. In: Brundsen D., Prior D.B. (Eds.), Slope Instability. Wiley, New York, 257-361.

Lebourg T., Riss J., Fabre R., Clement B. 2003. Morphological Characteristics of till formation in relation with mechanical parameters. Mathematical Geology: 35, 835-852.

Murray R.S. 1983. Statistics, 2nd edition. McGraw-Hill.

Nash E.J. 1960. A unit hydrograph study, with particular reference to British catchments. Proceedings Institution of Civil Engineers: 17, 249-282.

O'Brien J.S., Julien P.Y. 1985. Physical processes of hyperconcentrated sediment flows. Proceeding of the Speciality Conference on Delineation of Landslides, Flash Flood and Debris Flow Hazard in Utah. Utah Water Research Laboratory: 260-279.

O'Brien J.S., Julien P.Y., Fullerton W.T. 1993. Two-dimensional water flood and mudflow simulation. Journal of Hydraulic Engineering: 119, 244-261.

O'Brien J.S. 2001. Flo-2d Users Manual.

Pierson T.C., Costa J.E. 1987. A rheologic classification of subaerial sediment-water flows. In Costa, J.E. and Wieczorek, G.F. (eds.), Debris flows/avalanches: process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology: 7, 1-12.

Razay A.H., Warwick W. 1997. ArcView GIS/Avenue programmers reference: class hierarchy quick reference and 101+ scripts, 2nd edn., OnWord Press, Santa Fe, p. 524.

Rickenmann D., Zimmermann M. 1993. The 1987 debris flows in Switzerland: documentation and analysis. Geomorphology: 8, 175-189.

Savage S.B. 1998. Analyses of slow high-concentration flows of granular materials. Journal of Fluid Mechanics: 377, 1-26.

Schilling S.P. 1998. LAHARZ: GIS programs for automated mapping of Lahar-Inundation Hazard Zones. U.S. Geological Survey Open –File Report: 98-638, 1-84.

Seong K. 2002. A study on the effective hydraulic conductivity of an anisotropie porous medium. Journal of Mechanical Science and Technology: 16, 959-965.

Syanozhetsky T.G.V., Beruchashvili G.M., Kereselidze N.B. 1973. Hydraulics of rapid turbulent and quasilaminar (structural) mudstreams in deformed bed with abrupt slopes. In Proc Istanbul Conference of the International Association of Hydrological Scientists: 1, S, 507-515.

Takahashi T. 1991. Debris flows. IAHR Monograph, Balkema, Rotterdam, p. 165.

Tomasetti L., Zonta M.F., Marchelli L., Pallaveri T. 2004. Hydrogeological hazard: the experience of the autonomous Province of Trento in hazard detection and management on urbanised alluvial fan. Internationales Symposion INTERPRAEVENT 2004 - RIVA/TRIENT. IX, 262-273.

Ya-Lun C. 1969. Statistical Analysis, 2nd edn. Holt, Rinehart and Winston, New York.

Zeller M., Fullerton W.T. 1983. A theoretically-derived sediment transport equation for sandbed channels in arid regions. In: Li R.M. and Lagasse F.P. (Eds.), Proceedings of the D. B. Simons Symposium on Erosion and Sedimentation, Colorado State University and ASCE, 1134-1148.