Debris flow susceptibility zoning: an approach applied to a study area

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Summary

Landslide susceptibility analysis allows drawing the susceptibility maps of an area, where the predicted areas involved by rapid landslides are drafted. The paper shows the susceptibility zoning of debris flows performed in an area in the Province of Reggio Calabria (Italy), regularly and historically involved by rapid flow-like landslide events. In particular, the source areas of landslides have been predicted using an heuristic method based on observed phenomena and on geological/geomorphological setting of the area (detailed and validated in field thematic maps). Then, propagation phase of debris flows has been analysed by an advanced method (numerical model) to assess the path, the travel distance and velocity of flowing mass. The obtained results represent a preliminary level of landslide susceptibility zoning of the area, developed on the base of nowadays available data, on which more sophisticated studies can be developed.

Keywords: debris flow, susceptibility descriptors, rheological law, numerical analyses, susceptibility zoning

Introduction

Debris flows are very rapid to extremely rapid surging flows of saturated debris in steep channels with strong entrainment of material and water from the flow path [Hungr *et al.*, 2001, 2014; Jacob *et al.*, 2005]. They are distinct from other types of landslides because they occur periodically on established channels, usually gullies and first- or second order drainage channels. Thus, debris flow hazard is specific to a given path and deposition area ("debris fan"). The above aspects, and the periodicity of occurrence at the same location, influence the methodology of hazard studies [Hungr *et al.*, 2001, 2014; Jacob *et al.*, 2005].

An important part of any landslide hazard or risk assessment is the quantitative estimate of post-failure motion ("runout") including travel distance, flow height and flow velocity. Several approaches have been developed to model fast gravitational mass movements in order to assess their characteristics, intensities and run out. The available methods give a good systematic approach to assessing the spreading, extension and impact that a landslide can generate. These methods can be divided into empirical, analytical and numerical methods. A good overview of methods for run-out modeling is given by Hürlimann *et al.* [2008] and Hungr [2016].

In particular, numerical models are based on fluid mechanics and solve the equations of mass and momentum conservation numerically after discretizing them in both space and time. The stresses in the momentum conservation equation are determined from the assumed constitutive law of the flowing material. Most models are based on a "continuum approach" that considers the loose, unsorted and multiphase material of a landslide as a continuum [Pastor *et al.*, 2012].

The depth-averaged shallow water equation approach using different solvers has been applied commonly for numerical simulations of rapid mass movements over complex topographies [Crosta *et al.*, 2006; Pastor *et al.*, 2009]. Depth averaging allows representing the rheology of the flow as a single term that expresses the frictional forces that act at the interface between the flow and the channel bed.

In the framework of the continuum and discontinuum methods, the depth-integrated SPH method proposed by Pastor *et al.* [2009] is particularly suitable for analysing landslides that have average depths which are small in comparison with their length or width. The mathematical model of SPH method proposed by Pastor *et al.* [2009] is based on v-p_w Biot-Zienkiewicz model. Assuming that for flow-like landslides the average depths are small if compared with their length or width, it is possible to simplify the 3D propagation model described above by integrating its equations along the vertical axis. In this way, the Biot-Zienkiewicz equations for non-linear materials and large deformation problems are coupled to various constitutive models (Bingham, Voellmy, Mohr-Coulomb, etc.), obtaining a 2D depth-integrated model, which presents an excellent combination of accuracy and simplicity and provides information about propagation, such as average velocity or depth of the flow along the path.

The numerical model used for the mathematical problem's resolution is the smoothed particle hydrodynamics method (SPH). The SPH model is a mesh-free method that provides an interesting and

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 DOI:10.19199/2017.2.0557-1405.047

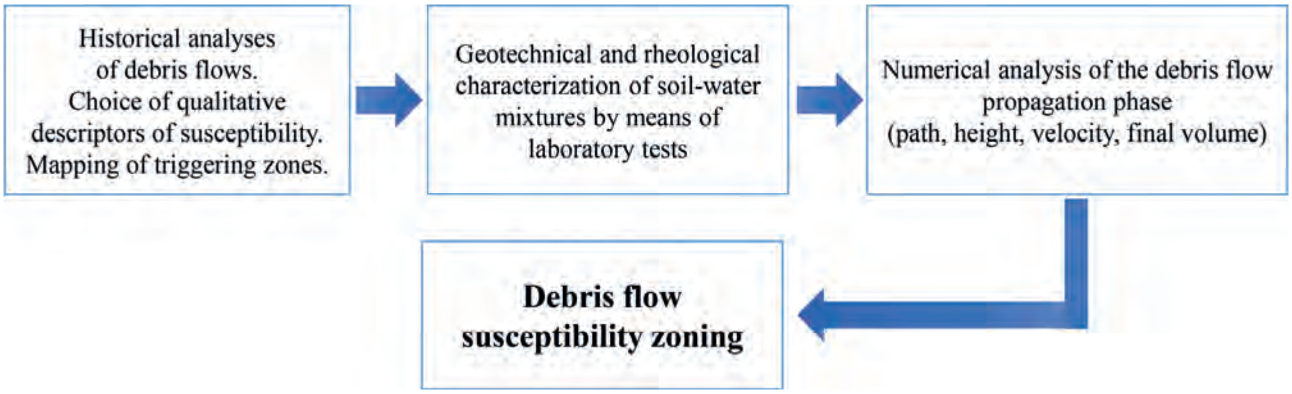


Fig. 1 – Flow chart of the proposed approach.
Fig. 1 – Diagramma di flusso dell'approccio proposto.

powerful alternative to more classical numerical methods such as the finite elements method.

Smoothed particle hydrodynamics is based on discretized forms of integral approximations of functions and derivatives. The SPH method introduces the concept of 'particles', to which information concerning field variables and their derivatives is linked. In particular, smoothed particle hydrodynamics method is based on the possibility of approximating a given function f(x) and its spatial derivatives by integral approximations defined in terms of a kernel. In a second step these integral representations are numerically approximated by a class of numerical integration based on a set of discrete points or nodes, without having to define any "element".

In order to simulate entrainment of material from the path, PIRULLI and PASTOR [2012] have formulated several algorithms. A number of much more sophisticated solutions have appeared in recent years, based on treating the fluid and solid phases of the flow separately using mixture theory (*e.g.* IVERSON and GEORGE, 2014).

The study of post-failure motion ("runout") including travel distance, flow height and flow velocity enables to obtain a spatial prediction for landslides and it contributes significantly in the landslide susceptibility mapping inside the framework of risk assessment (*e.g.* LEE *et al.,* 2004; HUNGR *et al.,* 2005; FELL *et al.,* 2008a). The susceptibility maps assist planners, local administrations, and decision makers in disaster planning. Among the approaches available in literature, the term "susceptibility" does not assume the same meaning. In the paper, the susceptibility has been considered, according to the approach of FELL *et al.* [2008a], as a quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landslides. Although it is expected that landslides will occur more frequently in the most susceptible areas, in the susceptibility analysis, the time in which landslides have occurred is not taken into account. It has been taken into account in the landslide hazard considering the return period.

In the paper, the susceptibility has been considered as spatial probability of occurrence but not temporal (hazard), and the susceptibility analyses have been based on two assumptions that the past is a guide to the future, so that areas which have experienced landsliding in the past are likely to experience landsliding in the future and that the areas with similar topography, geology and geomorphology as the areas which have experienced landsliding in the past are also likely to experience landsliding in the future.

This paper shows a mixed approach to obtain susceptibility maps in an area located between Scilla and Favazzina (Reggio Calabria), which has been recurrently interested by rainfall-induced debris flows [GULLÀ *et al.,* 2005, 2006; MANDAGLIO *et al.,* 2016].

The source areas of the landslides have been predicted using an heuristic method based on available data (observed phenomena and on geological/geomorphological setting of the area). For this purpose, detailed and validated in field thematic maps have been used. The propagation phase of debris flows has been analysed by an advanced numerical model to assess the path, the travel distance and the velocity of flowing mass.

The proposed approach is summarized in the flow chart shown in figure 1, and it is composed by four stages:

a. Debris flow inventory mapping and prediction of source areas. Historical analyses of past debris flows have been performed in order to obtain the susceptibility descriptors. Therefore, predicted triggering zones have been identified taking into account areas with susceptibility descriptors like those of the past events. The results of this stage have been the base for the identification of areas where potential debris flows could occur.

b. Calibration of the rheological law. Geotechnical and rheological characterization of soil-water mixtures by means of laboratory tests has been carried out in order to calibrate the debris flow rheological law.
c. Analysis of debris flow propagation phase. The propagation phase has been studied by the numerical code SPH proposed by Pastor *et al.* [2009].
d. Debris flow susceptibility zoning. Numerical results allowed drawing the susceptibility maps. The maps show the debris flow paths and their boundaries and the main elements potentially at risk.

Study Area

In the present research, the tested area is a zone located between Scilla and Favazzina (Reggio Calabria, Italy), affected by several events of recurrent debris flow landslides. These events propagate in "V" shaped channels and, along them, material is entrained and large amount of water is available which causes the propagating mass to fluidize, even without liquefaction has occurred in landslide source areas.

The zone falls within an extremely complex area characterized by the presence of several tectonic structures, frequently intersected each other, crossing the rock masses belonging to the crystalline metamorphic basement of Aspromonte. The crystalline-metamorphic bedrock of the area is constituted by continental crust of the Aspromonte- Peloritani Unit, of Hercynian age [Pezzino *et al.*, 1990; Borrelli et *al.*, 2012], formed by a migmatitic complex intruded by granites which are alternated to biotitic paragneiss, often with traces of partial melting and migmatitic gneiss with high biotitic concentrations.

Referring to the test area, the main lithologies that typically outcrop are residual soils (reddish-brown silty-sandy blankets encapsulating very weathered rock fragments) that cover a crystalline bedrock. The slope stability conditions of the area are strongly controlled by the weathering degree of the rock masses [Gullà *et al.,* 2005; 2006], by the climatic conditions as well as by tectonic and geomorphic factors. Shallow landslides generally occur during the wet season and quickly evolve, following mechanisms classified as debris flows. The flows occurred periodically in steep channels with strong entrainments of material and water from the whole flow path.

The most part of sediments that form the coast were originated by such processes.

From the hydraulic point of view, it must be pointed out the strong erosive and transport capacity of the streams (*e.g.* Favazzina, Favagreca, Scirò, Condoleo, Prajalonga, Mancusi, Rustico) that is able to transport disruptive amount of water and debris [Mandaglio *et al.*, 2015; 2016].

In the last decade, the frequency of the damaging events increased and some shallow landslides severely affected the main elements at risks of the area (urbanized areas and transportation infrastructures such as Highway Salerno –Reggio Calabria A3, Main Road SS 18, Railway, SNAM plant) along the coastal zone.

Historical data of landslide events which occurred in the area have been provided by the Autorità di Bacino Regione Calabria (ABR) (updated at 2006) and by the data available on the Geoportale Nazionale (http://www.pcn.minambiente.it /GN/). These data have been catalogued according to IFFI Project (Inventory of landslides in Italy), whose target is to create a single information system for the landslides in Italy and the homogenization of the national data. Moreover, additional information available in literature on a real event have been used [Bonavina *et al.*, 2005].

Past events in the area occurred in 2001 and in 2005 producing extensive damage which involved various lifelines as shown in figure 2. Particularly, on 12 May 2001, debris flows were triggered by heavy rainfalls at the head of the Favagreca channel, respectively at 600 and 610 m above sea level in correspondence of two stream incisions which converge at about 400 m a.s.l. The debris flow runout hit the SNAM station of the methane pipeline, the main road SS 18 and the railway causing the derailment of the intercity train Turin - Reggio Calabria. Available studies [Bonavina *et al.,* 2005] have shown that the volumes at the end of the propagation were tripled respect to trigger one ($V_i \cong 1.130$ m^3) in the 2001 event. During the same event, a second debris flow, in an adjacent valley, has invested the A3 - Salerno Reggio Calabria at the Brancato tunnel. This debris flow has not been considered in the paper because the runout was outside the examined area.

On 31 March 2005, another debris flow activated on the slope overlooking the Favazzina village, causing several damages to the highway and the derailment of the intercity train ICN Reggio Calabria – Milan [Bonavina *et al.,* 2005].

In the above mentioned cases:

a. the phenomena have been classified as very rapid to extremely rapid debris flows;
b. the source areas were localized at the head of the channels, immediately below secondary roads;
c. in the source areas, the weathered soils produced from the metamorphic bedrock were mobilized;
d. the thickness of the involved material appeared to be less than 2 meters;
e. the landslide masses, channelled and fluidized by stream waters during the runout, were rapidly moved along steep channels with strong entrainment of material and water;
f. the deposition occurred on debris fans and the mass partially reached and deposited in the sea.

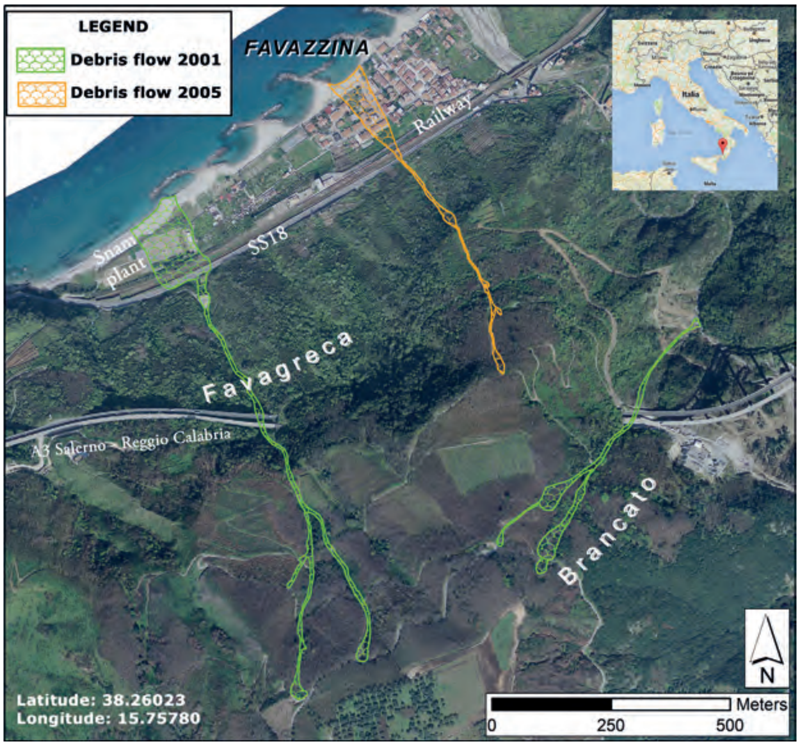


Fig. 2 – 2001 and 2005 rapid debris flows: triggering zones, propagation and accumulation areas.
Fig. 2 – Debris flow avvenuti nel 2001 e nel 2005: zone di innesco, aree di propagazione e accumulo.

Methodology

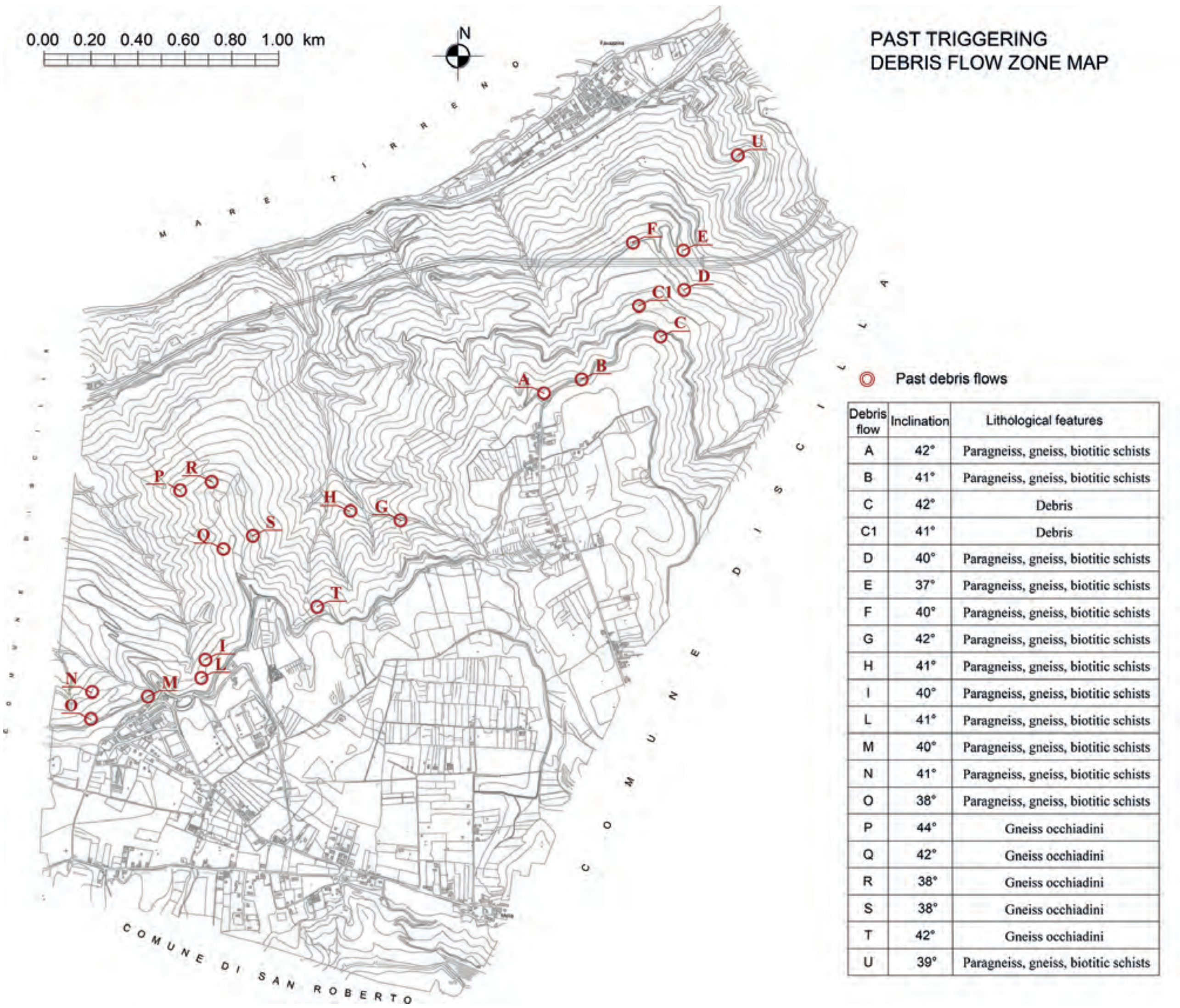
Debris flow inventory mapping and prediction of source areas

The landslide inventory mapping is an essential part of any landslide zoning. It involves the landslide location, classification, areal extent and state of activity. The landslide inventory mapping shows the distribution of existing landslides mapped from historical data of landslide occurrences, aerial photographs, and field surveys. For this purpose, intensive work should be carried out in order to collect data about landslides occurred and about additional information such as soil and rock geotechnical properties, geological features of triggering zones, and areal extent.

The collected data should be mapped and classified in term of landslide types as a function of triggering mechanism, movement type, involved material, slope morphology, and so on. In this way, it is possible to construct a landslide inventory where past landslides are mapped. The landslide zoning uses common descriptors to describe the degree of landslide susceptibility, hazard and risk. It is difficult to standardise descriptors of landslide susceptibility. In some situations, it may be sufficient to simply use two susceptibility descriptors, “susceptible” and “not susceptible”. Qualitative susceptibility assessment is based entirely on the judgement of the person carrying out the analysis. For example, qualitative susceptibility descriptors are field geomorphological analyses and index map or parameter maps. In the last case, the landslide susceptibility mapping occurs overlapping index maps with or without weighting [FELL *et al.*, 2008b]. Descriptors are parameters or combinations of parameters that are chosen according to: the scale of analysis and the related zoning purposes (information, advisory, statutory and design); the landslide types (potential or existing) and their characteristics.

For the studied area, historical data of occurred landslides (Fig. 3) have been analysed in order to obtain the lithological and inclination features of the triggering zones of first-failure landslides involving residual soils of the past debris flows. Slope inclinations have been evaluated by means of high resolution digital terrain model (interval contour of 2 m) of the area and the lithological features have been obtained by geological map (scale 1:5.000). In figure 3, the letters A, B, C, and C_1 refer to the event in 2001 while the letter F refers to the event in 2005.

The analysis of twenty past rapid events (Fig. 4), occurred between 2001 and 2005, has been performed in order to define the slope ranges of the events. The obtained results showed that the most part of the events occurred on slope ranges of 38°-40° and 41°-43°, with frequency of the number of the events equal to 40% and 50%, respectively. Moreover, the past events occurred on debris and on alteration soils coming from paragneiss, gneiss and biotitic schists, and gneiss occhiadini.



Debris flow	Inclination	Lithological features
A	42°	Paragneiss, gneiss, biotitic schists
B	41°	Paragneiss, gneiss, biotitic schists
C	42°	Debris
C1	41°	Debris
D	40°	Paragneiss, gneiss, biotitic schists
E	37°	Paragneiss, gneiss, biotitic schists
F	40°	Paragneiss, gneiss, biotitic schists
G	42°	Paragneiss, gneiss, biotitic schists
H	41°	Paragneiss, gneiss, biotitic schists
I	40°	Paragneiss, gneiss, biotitic schists
L	41°	Paragneiss, gneiss, biotitic schists
M	40°	Paragneiss, gneiss, biotitic schists
N	41°	Paragneiss, gneiss, biotitic schists
O	38°	Paragneiss, gneiss, biotitic schists
P	44°	Gneiss occhiadini
Q	42°	Gneiss occhiadini
R	38°	Gneiss occhiadini
S	38°	Gneiss occhiadini
T	42°	Gneiss occhiadini
U	39°	Paragneiss, gneiss, biotitic schists

Fig. 3 – Map of the past real debris flows occurred in the studied area.
Fig. 3 – Mappa delle aree di innesco di debris flow avvenuti nell'area di studio.

On the base of available information, the source areas of potential landslides have been predicted using an heuristic method based on observed phenomena and on lithological (Fig. 5), inclination (Fig. 6) and geomorphological (Fig. 7) setting of the area. In particular, detailed and validated in field thematic maps (maps drawn for the design of the new double three-phase 380 kV powerline) have been used to evaluate potential triggering areas of debris flows. For this purpose, the slope inclinations, lithological features and geomorphological evidences (crowns, deep eroded gullies, steep and collapse slopes) have been selected as qualitative susceptibility descriptors. The potential triggering zones of debris flows (Fig. 8) have been obtained overlapping three thematic layers (Figs. 5, 6, 7).

Potential and past debris flow triggering zones of the area are shown in figure 9, where blue squares represent the predicted potential triggering zo-

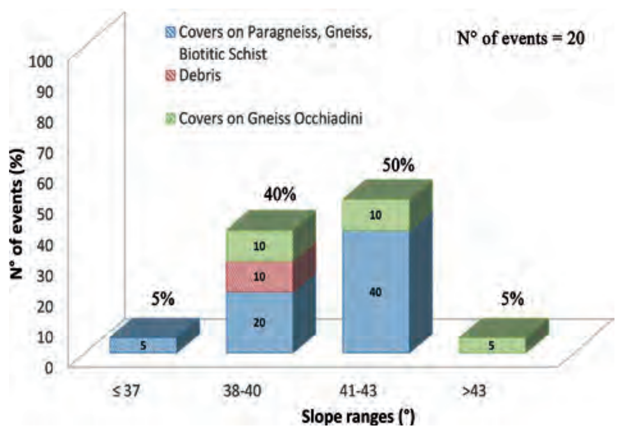


Fig. 4 – Frequency of the number of events versus slope ranges and involved lithology.
Fig. 4 – Frequenza del numero di eventi in funzione degli intervalli di inclinazione e delle litologie coinvolte.

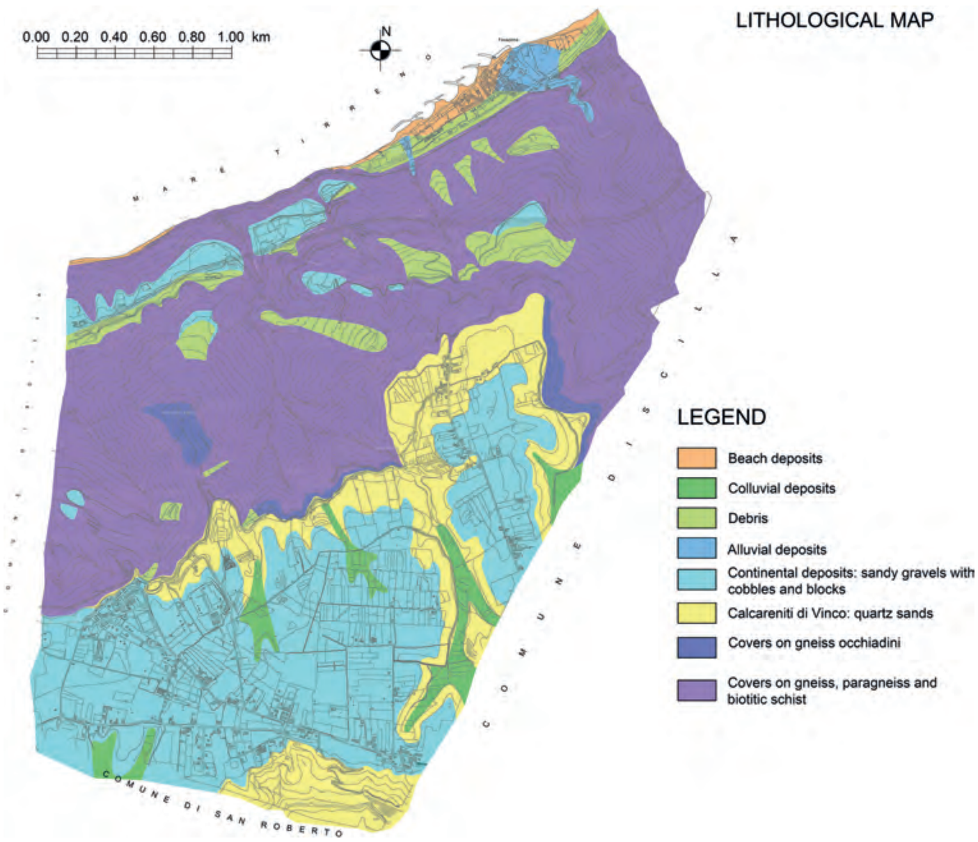


Fig. 5 – Lithological map of the studied area.
Fig. 5 – Mappa litologica dell'area di studio.

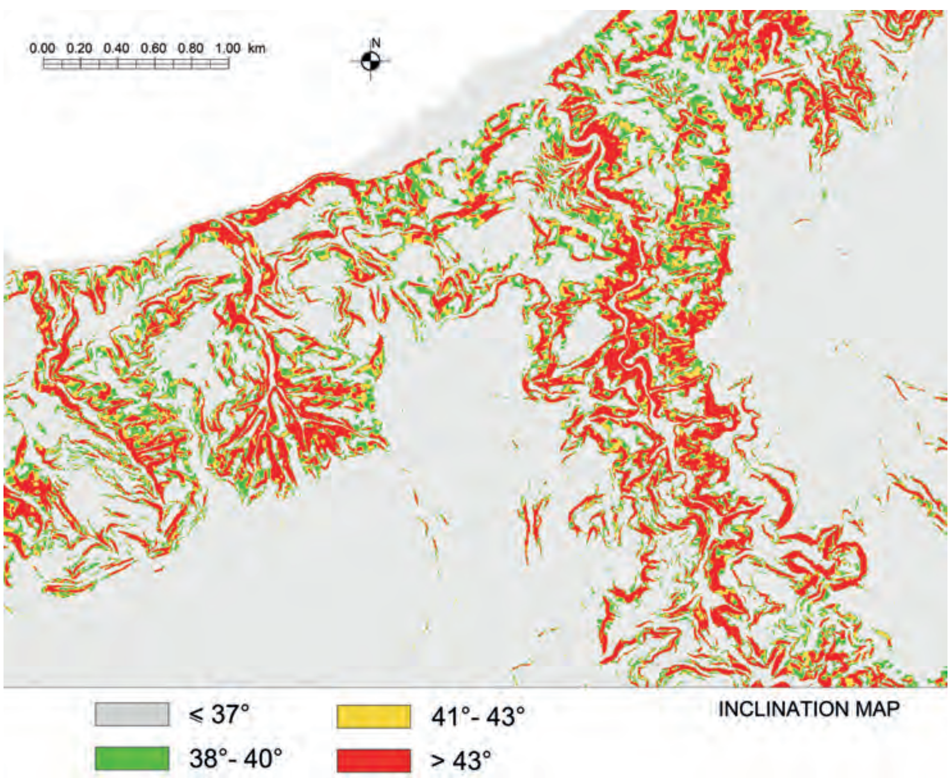


Fig. 6 – Inclination map of the studied area.
Fig. 6 – Mappa delle inclinazioni dell'area di studio.

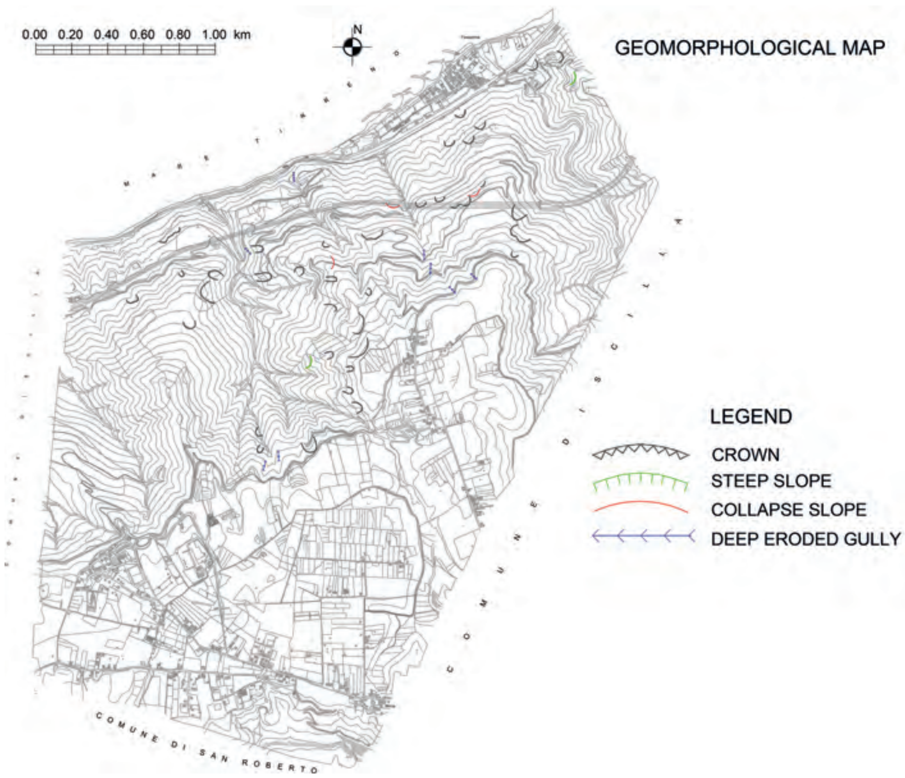
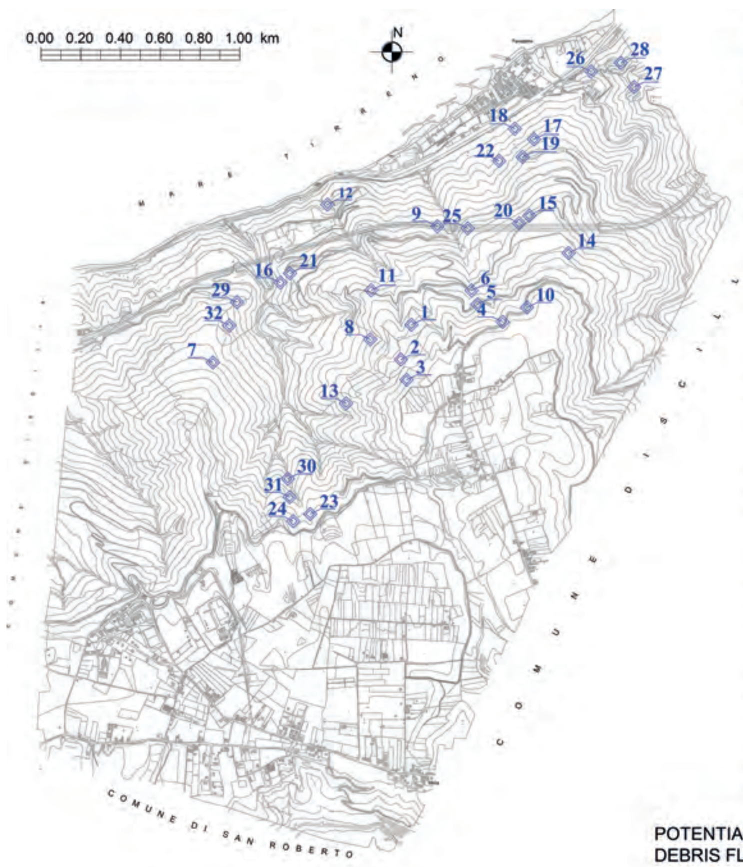


Fig. 7 – Geomorphological map of the studied area.
Fig. 7 – Mappa geomorfologica dell'area di studio.



Debris flow	Inclination	Lithological features	Geomorphological evidences
1	37°	Paragneiss, gneiss, biotitic schists	Crown
2	43°	Paragneiss, gneiss, biotitic schists	Crown
3	37°	Paragneiss, gneiss, biotitic schists	Crown
4	42°	Paragneiss, gneiss, biotitic schists	Deep eroded gully
5	40°	Paragneiss, gneiss, biotitic schists	Deep eroded gully
6	44°	Paragneiss, gneiss, biotitic schists	Deep eroded gully
7	37°	Debris	Crown
8	39°	Debris	Crown
9	39°	Paragneiss, gneiss, biotitic schists	Collapse slope
10	41°	Debris	Deep eroded gully
11	41°	Paragneiss, gneiss, biotitic schists	Collapse slope
12	37°	Paragneiss, gneiss, biotitic schists	Deep eroded gully
13	43°	Paragneiss, gneiss, biotitic schists	Steep slope
14	44°	Paragneiss, gneiss, biotitic schists	Crown
15	38°	Paragneiss, gneiss, biotitic schists	Collapse slope
16	42°	Paragneiss, gneiss, biotitic schists	Deep eroded gully
17	39°	Paragneiss, gneiss, biotitic schists	Crown
18	40°	Paragneiss, gneiss, biotitic schists	Crown
19	38°	Paragneiss, gneiss, biotitic schists	Crown
20	37°	Paragneiss, gneiss, biotitic schists	Crown
21	44°	Paragneiss, gneiss, biotitic schists	Crown
22	37°	Paragneiss, gneiss, biotitic schists	Crown
23	37°	Gneiss occhiadini	Deep eroded gully
24	41°	Gneiss occhiadini	Deep eroded gully
25	39°	Paragneiss, gneiss, biotitic schists	Crown
26	43°	Paragneiss, gneiss, biotitic schists	Crown
27	41°	Paragneiss, gneiss, biotitic schists	Steep slope
28	42°	Paragneiss, gneiss, biotitic schists	Crown
29	39°	Paragneiss, gneiss, biotitic schists	Crown
30	42°	Paragneiss, gneiss, biotitic schists	Crown
31	44°	Paragneiss, gneiss, biotitic schists	Crown
32	40°	Paragneiss, gneiss, biotitic schists	Crown

POTENTIAL TRIGGERING
DEBRIS FLOW ZONE MAP

Fig. 8 – Potential debris flow map of the studied area.
Fig. 8 – Mappa dei debris flow potenziali dell'area di studio.

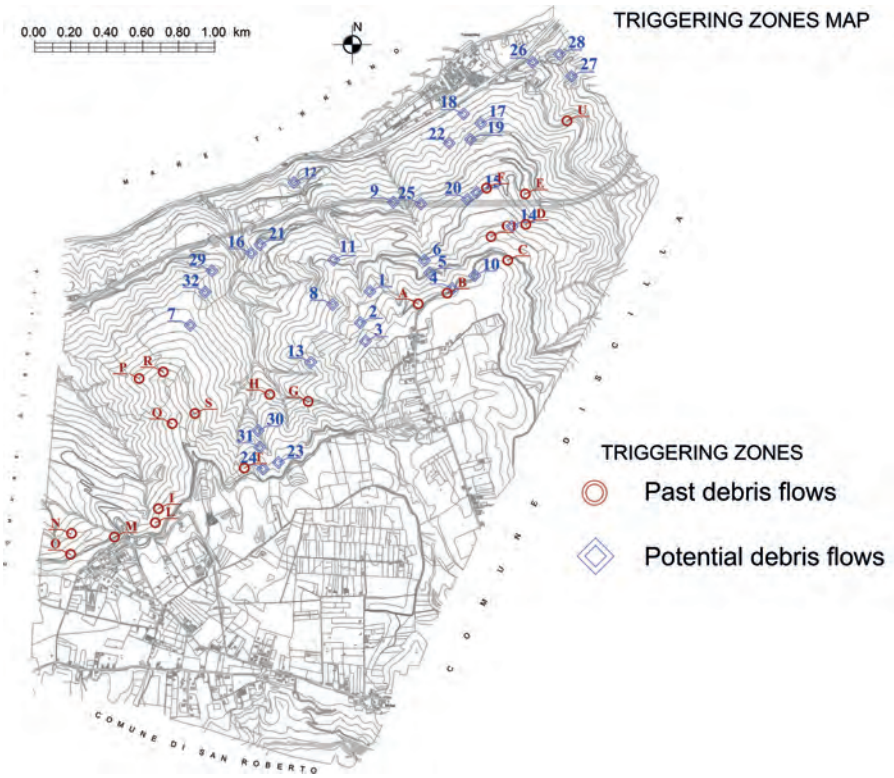


Fig. 9 – Triggering zone map of the studied area.
Fig. 9 – Mappa delle aree di innesco dell'area di studio.

nes while red circles represent the zones where the past debris flows occurred.

The mapping shown in figure 9 represents the result of the first stage in the proposed approach.

Calibration of the rheological law

In order to study the propagation phase, it is important to define the rheological model of the debris flow mixture. Definition of rheological model is fundamental for the numerical analyses to evaluate the debris flow paths (runout), velocities and heights during the propagation phase.

The soil involved in the rapid debris flows occurred in the studied area has been sampled in three different zones near the triggering zones of real past events (Events A and F, Fig. 3). Considering that the past events of debris flows occurred on the same soils, due to the limited variability of lithological and geotechnical features of outcropping soils (residual soils), the sampled soil has been assumed representative as trigger soil mass.

The plastic index and liquid limit of the sampled soil were 9.23 % and 33.27%, respectively. The percentage of different fractions were: Sand = 30 %, Silt = 45%, Clay = 25%. The soil has been classified according to the Unified Soil Classification System (USCS) as inorganic silt of medium compressibility with sand (ML). Besides, in order to obtain the mixture rheological law, viscometer tests have been performed using the finer percentage (fine sandy, silty and clayey fractions) of soils. Tests have been carried out on soil-water mixtures changing the solid concentration by volume C_v, defined as the ratio between the solid particles volume and the total volume of the specimen. In particular, between 35% and 45%.

The selection of a particular rheological model is difficult, and several models can provide similar results. Several models have been developed from experimental data got with rheometer, from theoretical considerations and from field observations. Basically, there are different models dedicated to the behavior of fluidized geomaterials and the most commonly used ones are: the frictional-turbulent "Voellmy" resistance proposed initially for snow avalanches and used for granular cohesionless materials with or without the presence of a pore fluid; the visco-plastic Bingham-type resistance relationship applicable for plastic clay-rich material [MALET *et al.,* 2004; PASTOR *et al.,* 2009]. According to RICKENMANN *et al.* [2006], a clay fraction (particle size less than 40 μm) greater than 10% is necessary for a flow material to behave like a Bingham fluid.

For the studied case, previously [GIOFFRÈ *et al.,* 2016], a parametric analysis using Voellmy model and Bingham model, was carried out, showing that

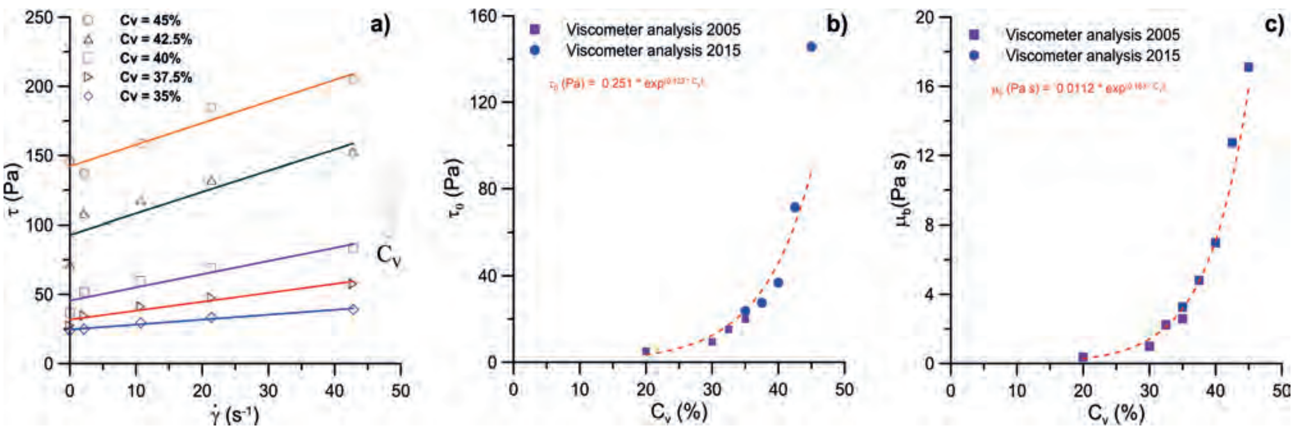


Fig. 10 – Viscometer results: Shear stress versus shear rate as a function of C_v a); Yield stress τ_0 versus solid concentration by volume C_v b); viscosity μ_b versus solid concentration by volume C_v c).

Fig. 10 – Risultati delle analisi con viscosimetro: Sforzo di taglio in funzione del gradiente di velocità al variare di C_v a); Tensione di snervamento τ_0 in funzione della concentrazione solida in volume C_v b); viscosità μ_b in funzione della concentrazione solida in volume C_v c).

the last one represents better the zoning resulting from the real event of 2001.

Once the model was selected, viscometer laboratory tests have been performed to derive the Bingham model parameters (τ_o and μ_b) as a function of the solid concentration (C_v). The figure 10a shows that the shear stress linearly increases with increasing of the shear rate. Moreover, results show that an increase of C_v leads to an increase of the shear stress.

The viscous Bingham law formulation is:

$$\tau = \tau_0 + \mu_b \cdot \dot{\gamma} \quad (1)$$

where τ is the shear stress, τ_0 is yield stress, μ_b is the Bingham viscosity and $\dot{\gamma}$ is the shear rate.

The trends of the yield stress and of the viscosity as a function of the solid concentration by volume are shown in figures 10b and 10c.

The results show that both the yield stress (τ_0) and the viscosity (μ_b) increase exponentially with increasing of the solid concentration by volume, according to equations, as follows:

$$\tau_0 = 0{,}251 \cdot e^{(0{,}132\ C_v)} \quad (2)$$

$$\mu_b = 0{,}0112 \cdot e^{(0{,}163\ C_v)} \quad (3)$$

The equations are applicable to flows with C_v less than 60 % [PIERSON *et al.*, 1987].

Analysis of debris flow propagation phase

The analysis of the rapid debris flow propagation phase is the third stage of the proposed approach. The distinctive features of these landslides are strictly related to the mechanical and rheological properties of the involved materials, which are responsible together with slope morphometry for long travel distances and the high velocities (order of meters/second) that the mass may attain.

The prediction of both run out distances and velocities through mathematical modelling of the propagation stage can notably reduce losses inferred by these phenomena, as it provides a tool for defining the threatened areas, and for working out the information for the identification and design of appropriate protective measures [MORACI *et al.*, 2015].

In this study, the numerical model of PASTOR *et al.* [2009] has been used to assess the path, the travel distance and the velocity of flowing mass. Numerical simulations of the propagation phase have been performed for the past and potential triggering zones shown in figure 9.

In the SPH numerical code, the bed erosion process is considered implementing the erosion law of HUNGR [1995] using the "growth rate" E_s, that represents the bed-normal depth eroded per unit flow depth and unit displacement, defined as:

$$E_s = \frac{\ln\,(V_{fin}/V_0)}{d} \quad (4)$$

where V_{fin} is the final volume of the mobilized material, V_0 is the initial volume of the debris flow and d is the travelled distance by debris flow. The numerical code used does not allow us to modify E_s along the path of debris flow [PASTOR *et al.*, 2009; CUOMO *et al.*, 2014]. Therefore, several numerical simulations have been carried out using different values of "growth rate".

In order to validate the results obtained by means of viscometer tests, numerical back-analyses ha-

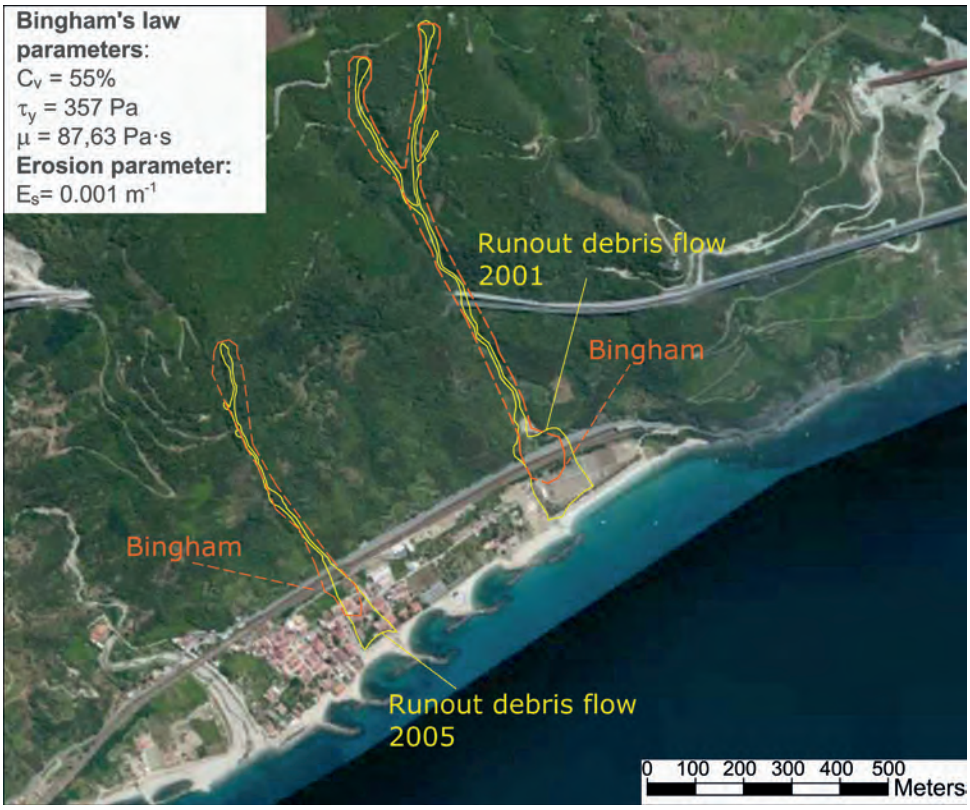


Fig. 11 – 2001 and 2005 Favazzina debris flows: comparison between real (yellow lines) and numerical (dotted lines) zoning.
Fig. 11 – Debris flow del 2001 e del 2005 nell'area di Favazzina: confronto tra la perimetrazione reale e quella ottenuta numericamente.

ve been performed on past debris flow occurred in the study area of Favazzina. In particular, the debris flow occurred in May 2001 has been simulated as it is well documented in the literature [BONAVINA *et al.,* 2005].

For analysing the debris flows, the conditions that occurred on event of May 2001, which affected the Favagreca river for which it was possible a better reconstruction of the geometry and of the volumes of detached mass, were taken into account. In particular, the following parameters were known: initial volume of the detached mass (1130 m^3); final volume at the end of the path (V_{fin}=3V_0); pre-event digital terrain model of the study area.

The validation of the numerical model was based on a trial and error selection of rheological parameters and of erosion coefficient for the debris flow occurred in May 2001. These values obtained for the debris flow of May 2001 were also used for the debris flow occurred in March 2005 because for this events similar information were not available.

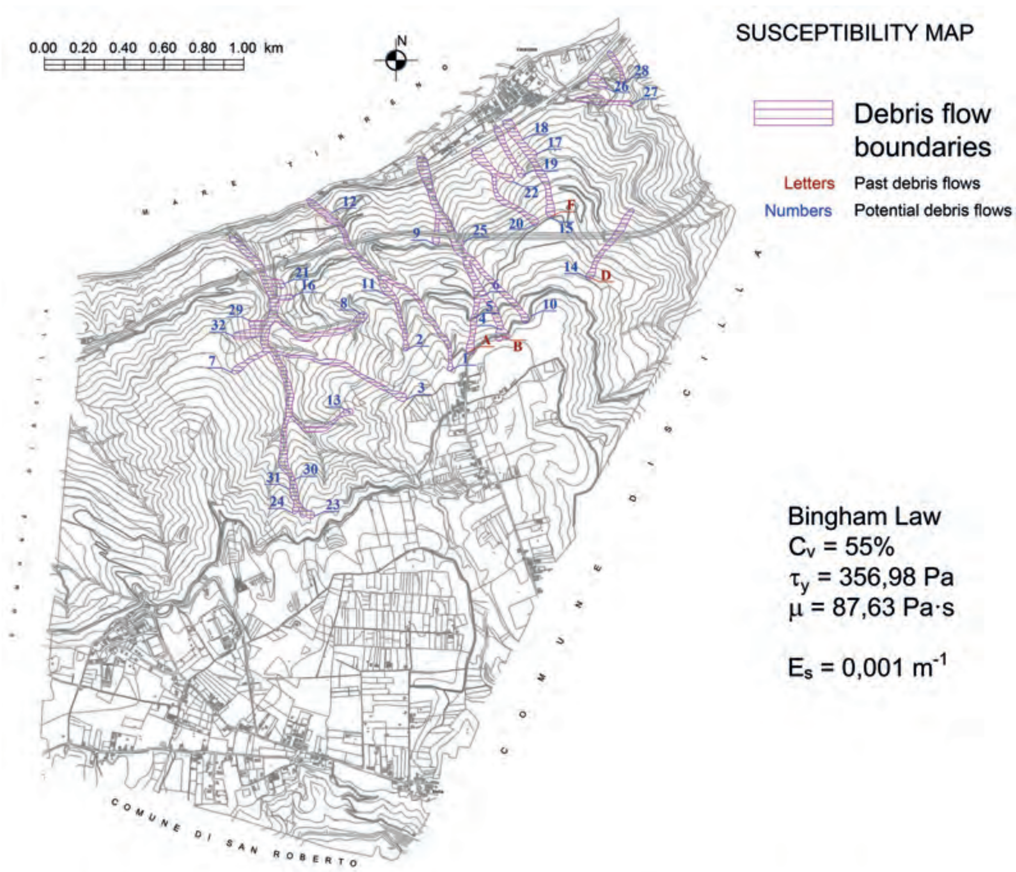
The analyses on the debris flows were carried out assuming the Bingham rheological parameters (yield stress τ_0 and viscosity μ_b) evaluated by means of equations (2) and (3) obtained by the viscometer tests for different values of solid concentration by volume C_v (40-60%). The erosion coefficient E_s, assumed equal to 0.001 m^{-1}, was obtained by the equation (4). Figure 11 shows the results of numerical simulations, performed using C_v =55% and E_s = 0.001 m^{-1}, that well fit the real zoning of the area involved in the debris flows of 2001 and 2005 (yellow lines). It can be noticed that the Bingham rheological law well reproduces the runout distances and the geometrical characteristics (shape, path, runout zones) of the analysed real debris flows. Differences can be noticed at the end of runout zones but they are due to low definition of DEM in these areas, that are extensively urbanized.

Results

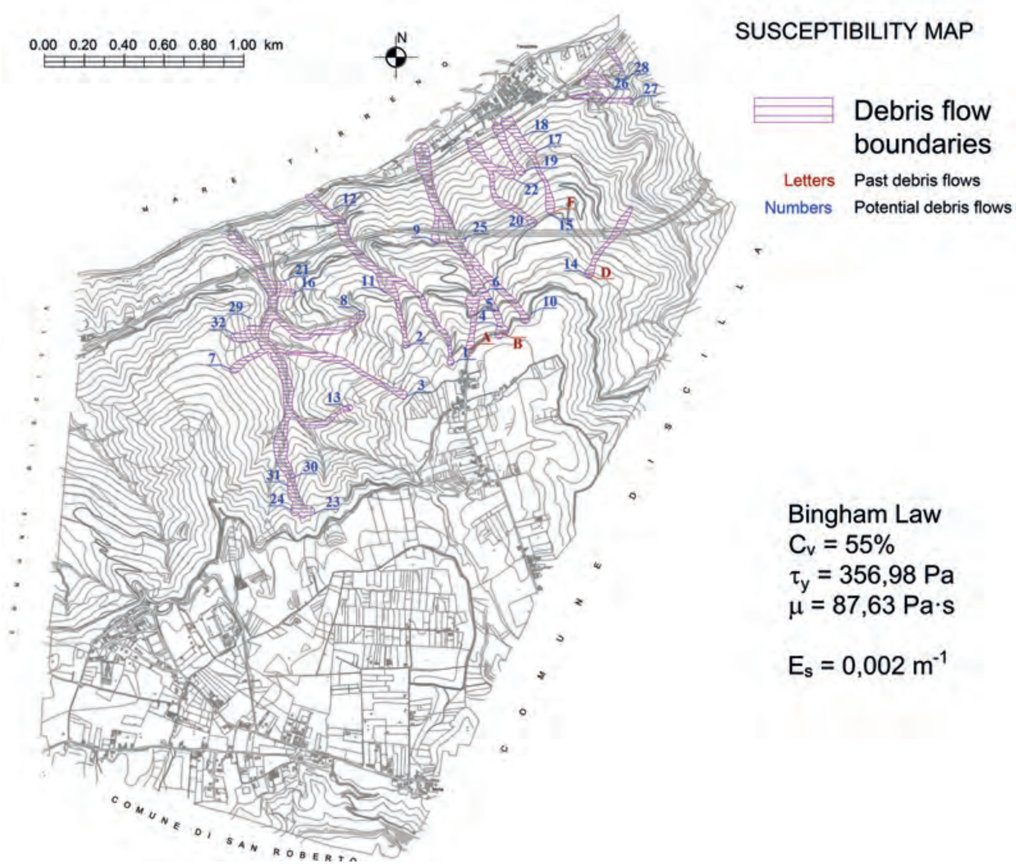
Debris flow susceptibility zoning

In order to draw the debris flow susceptibility maps, several numerical simulations of the propagation phase of the potential and real triggering zones previously identified (Fig. 9) have been performed and the run-out zones and debris flow paths have been marked.

The Bingham rheological parameters have been varied as a function of the solid concentration by volume C_v and the range of variation of C_v has been chosen considering the typical values of debris flows [PIERSON *et al.,* 1987]. The Hungr erosion coefficient E_s has been changed between



a)



b)

Fig. 12 – Susceptibility maps of the studied area with C_v=55% for E_s=0.001m^{-1} a) and E_s=0.002m^{-1} b).

Fig. 12 – Mappe di suscettibilità dell'area in esame per C_v=55% per E_s=0.001m^{-1} a) e E_s=0.002m^{-1} b).

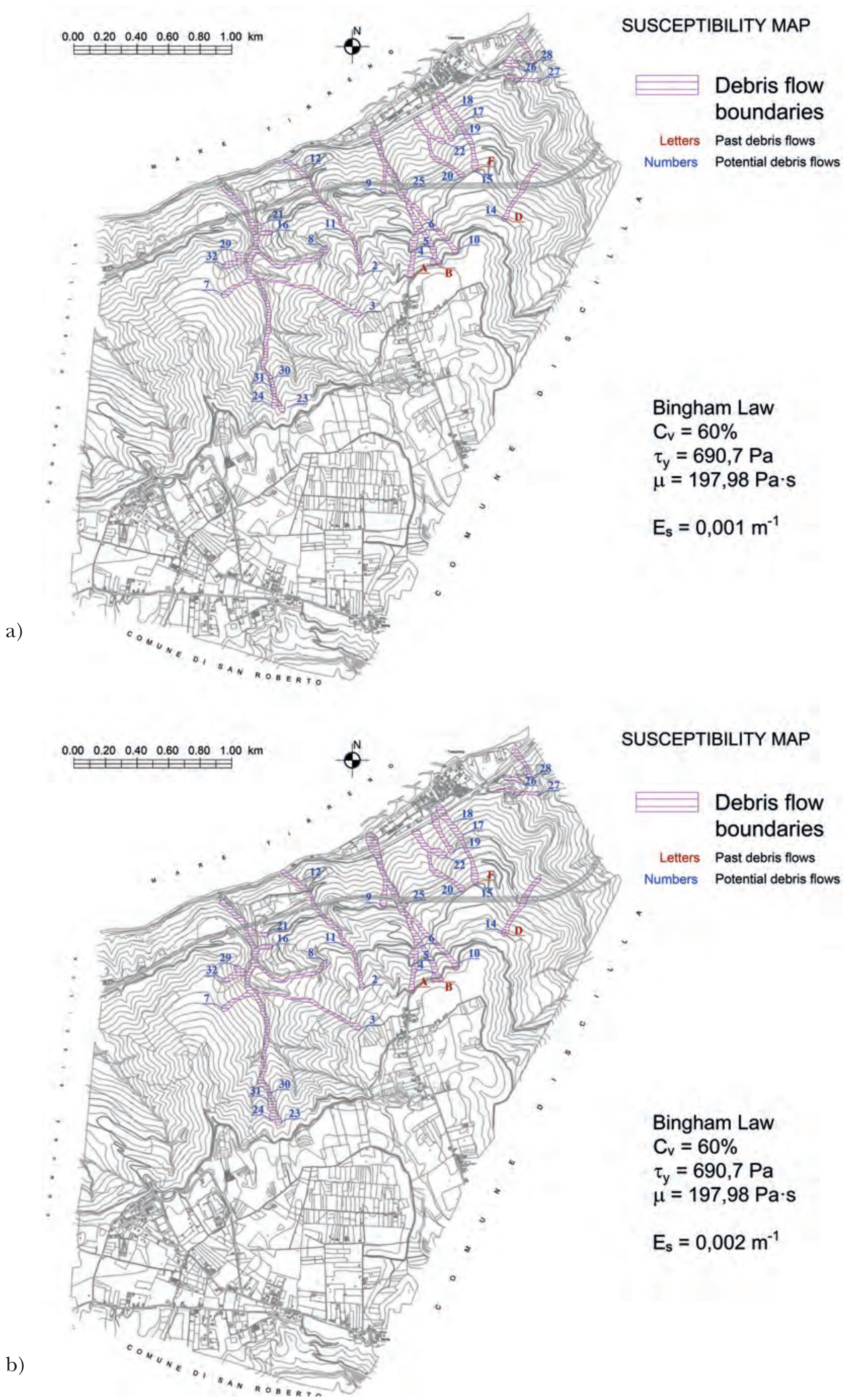


Fig. 13 – Susceptibility maps of the studied area with C_v=60% for E_s=0.001m^{-1} a) and E_s=0.002m^{-1} b).
Fig. 13 – Mappe di suscettibilità dell'area in esame per C_v=60% per E_s=0.001m^{-1} a) e E_s=0.002m^{-1} b).

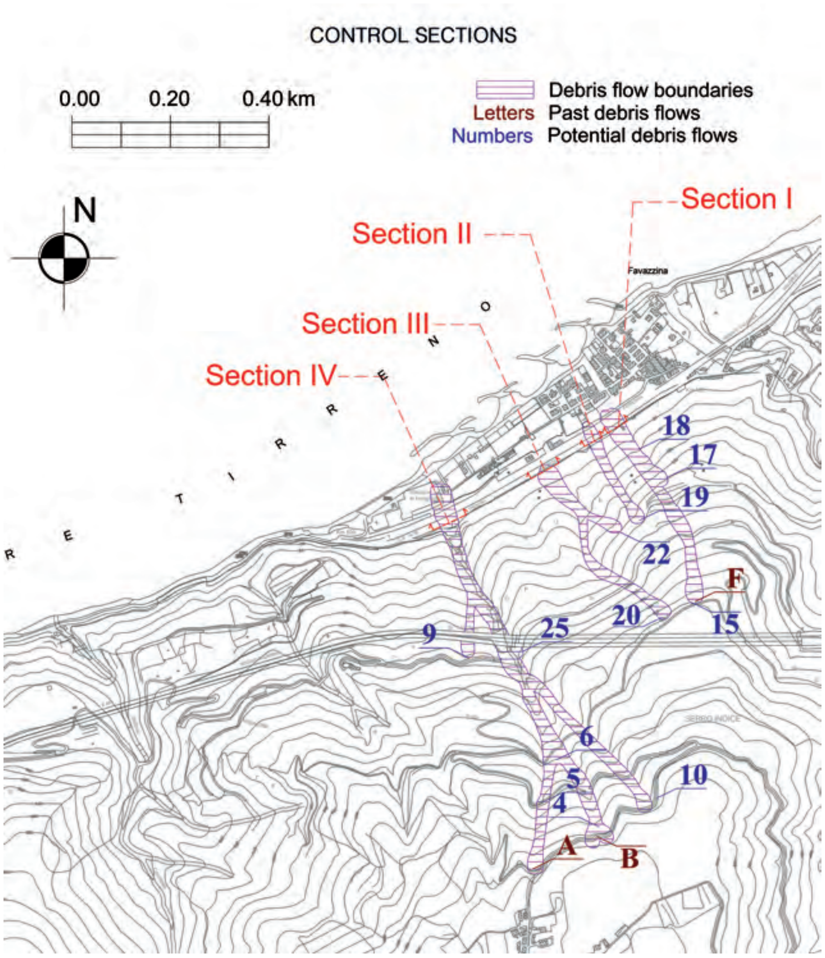


Fig. 14 – Control sections.
Fig. 14 – Sezioni di controllo.

0.001 m^{-1} and 0.002 m^{-1}. The initial mobilized volume depends on the amount of rainfall and its cumulative time trend as well as on the morphometry of the specific slope where it triggered. On the base of the geomorphological analyses performed, the initial volume of the detached mass of debris flow 2001 resulted one of the major volumes detached in the studied area. Therefore, this value has been assumed on safe side as initial volume of the potential and real triggering zones in the propagation phase for drawing the susceptibility maps.

Ten debris flows susceptibility maps have been obtained for different values of solid concentration by volume C_v (40-45-50-55-60%) and for different E_s (0.001 m^{-1} - 0.002 m^{-1}). Figures 12-13 show the debris flows susceptibility maps drawn for the solid concentration by volume C_v equal to 55% and 60% and E_s equal to 0,001 m^{-1} and 0,002 m^{-1}. The maps report the debris flow path boundaries (magenta zones), obtained by numerical simulations. The zoning has been performed overlapping for the channels made of more than one incision the obtained numerical results in each simulations.

Comparison between maps with the same C_v value and different E_s shows that the propagation zones and the run-out areas are wider in the case of E_s equal to 0,002 m^{-1}, as expected.

Moreover, the maps with solid concentration by volume equal to 60% (Fig. 13) show a higher degree of channelling of the debris flows than those with solid concentration by volume equal to 55% (Fig. 12); this is due to greater values of velocity obtained for C_v = 55% that produce greater spreading in terms of displacement of ‘particles’.

In order to choose a safety debris flow susceptibility map for the area, four control sections (I, II, III, IV), in correspondence to the main road SS18, have been chosen (Fig. 14). In these sections, the values of debris flows heights, final volumes and velocities, have been taken by the numerical simulations.

Tab. 1 – Results of numerical analysis obtained for Es 0,001m^{-1}, C_v 55% and C_v 60% in the control sections.
Tab. 1 – Risultati dell'analisi numerica ottenuti per Es 0,001m^{-1}, C_v 55% e C_v 60% nelle sezioni di controllo.

Section	ID Debris flow	C_V	55%			60%		
		d	V_{fin}/V_0	h_{runout} (v = 0)	$v_{c.s.}$	V_{fin}/V_0	h_{runout} (v = 0)	$v_{c.s.}$
		(m)	(-)	(m)	(m/s)	(-)	(m)	(m/s)
I	**F**	690	1,517	1,22	5,12	1,533	0,79	4,05
	17	345	1,348	1,00	5,60	1,349	0,95	2,69
	18	290	1,291	0,99	5,13	1,288	1,05	2,42
II	**19**	385	1,424	0,80	8,50	1,392	0,92	6,40
III	**20**	630	1,649	1,07	4,46	1,564	1,02	4,30
	22	380	1,407	0,60	3,90	1,373	0,79	1,60
IV	**A**	1080	3,157	2,13	7,15	3,031	2,06	6,22
	4	1000	2,681	2,22	6,98	2,645	1,67	5,76
	5	860	2,182	1,33	7,03	1,749	1,28	5,56
	6	800	1,395	1,00	7,09	1,401	0,72	5,40
	9	500	1,468	1,12	5,47	1,397	1,11	3,50
	10	1016	2,695	2,53	7,08	2,490	1,15	6,09
	25	500	1,524	2,30	4,25	1,377	1,32	4,07

ID Debris flow= debris flow identification; d = travelled distance; V_{fin} = debris flow final volume; V_0 = debris flow initial volume; h_{runout} (v = 0) = debris flow height in the deposition area (flow velocity =0); $v_{c.s.}$ = debris flow velocity in the control section.
ID Debris flow= identificativo del debris flow; d = lunghezza del percorso debris flow; V_{fin} = volume finale debris flow; V_0 = volume iniziale debris flow; h_{runout} (v = 0) = altezza del debris flow nella zona di deposizione (velocità del flusso = 0); $v_{c.s.}$ = velocità del debris flow nella sezione di controllo.

The results of numerical analysis obtained for C_v values equal to 55% and 60% and for E_s value equal to 0,001 m^{-1} in terms of debris flow height, volume and velocity values are shown in table I. These values are in accord with those measured for the debris flow of 2001. The results obtained for C_v equal to 55% and E_s equal to 0.001 m^{-1} show greater debris flow heights and velocities, so the debris flow susceptibility map of the studied area shown in figure 12a has been taken up in order to stay on the safe side.

Conclusions

In this paper, an approach to define the debris flow susceptibility of an area, where the lithological and geotechnical features have a limited variability, has been proposed. The used approach provided a good accuracy between predictions against observed data. In particular, the obtained susceptibility zoning maps based on susceptibility descriptors, laboratory tests and numerical analysis are in good agreement with the past events occurred in the area.

Considering that the choice on the most appropriate zoning method to adopt also depend on factors, such as the quality and accuracy of the available data within the area to be zoned, the proposed approach can be considered as a preliminary mixed approach. In fact, the triggering areas of landslides have been predicted using a heuristic method based on observed phenomena and on geological/geomorphological setting of the area whereas the path, the travel distance and velocity of flowing mass have been evaluated by application of a continuum-mechanics based numerical code.

The results provide a preliminary level of zoning on which more sophisticated studies based on deterministic methods including physically based model such as SHALSTAB [MONTGOMERY and DIETRICH, 1994] or TRIGRS unsaturated [SAVAGE *et al.*, 2004] must be developed. Therefore, the proposed approach can be used for information and advisory.

Acknowledgment

All authors have contributed in equal manner to the development of research and to the extension of memory. This research was financially supported by the Italian government within the framework of the

PRIN 2010-2011 Project titled “La mitigazione del rischio da frana mediante interventi sostenibili”.

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Zonazione della suscettibilità da frana di colata detritica: un approccio applicato a un’area studio

Sommario

L’articolo presenta un approccio per la zonazione della suscettibilità da frana di colata detritica applicato a un’area della provincia di Reggio Calabria (Italia), periodicamente soggetta a frane di colata rapida innescate da piogge. In particolare, utilizzando un metodo euristico basato sui fenomeni osservati e sulle caratteristiche geologiche/geomorfologiche dell'area in esame, sono state individuate le aree di potenziale distacco di colate detritiche. Successivamente, è stata analizzata con un metodo avanzato (modello numerico) basato sulla caratterizzazione geotecnica e reologica delle coltri di alterazione coinvolte nei fenomeni franosi, la fase di propagazione delle colate detritiche. In tal modo è stato possibile valutare, per ogni colata detritica potenziale o reale, il percorso e le caratteristiche cinematiche (altezza e velocità di propagazione) in corrispondenza di differenti sezioni di controllo poste in prossimità di elementi esposti.

I risultati ottenuti rappresentano un livello preliminare di zonazione della suscettibilità da frana dell’area in base al quale sviluppare studi più sofisticati volti alla mitigazione del rischio.