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# A COMPARISON BETWEEN PHYSICALLY-BASED MODELS AND A SEMIQUANTITATIVE METHODOLOGY FOR ASSESSING SUSCEPTIBILITY TO FLOWSLIDES TRIGGERING IN PYROCLASTIC DEPOSITS OF SOUTHERN ITALY

**ABSTRACT**: ANDRIOLA P., CHIRICO G.B., DE FALCO M., DI CRESCENZO G. & SANTO A., *A comparison between physically-based models and a semiquantitative methodology for assessing susceptibility to flowslides triggering in pyroclastic deposits of Southern Italy*. (IT ISSN 0391-9838, 2009).

Two well-known physically-based models, SHALSTAB and SINMAP, and a statistical approach have been applied to predict the susceptibility to flowslides in the pyroclastic cover of carbonatic ridges in Campania (Southern Italy). The results obtained with these different techniques, specifically concerning the prediction of potential source location, have been compared to explore potential applications and limitations.

The statistical approach has been applied to a database of 187 historical flowslides, whose characteristics have been analysed by means of a Semi-Quantitative Method (SQM). The statistical approach has produced more conservative results, by attributing high level of susceptibility to larger areas; moreover, it has proved to be more accurate in predicting the locations of the historical source areas of shallow landslides (i.e. of the real cases analysed). On the contrary, physically-based models have resulted more effective in considering the effects of local morphology, such as channels and convergent areas, but less accurate in predicting triggering locations on either planar or divergent slopes.

The primary limitation of the adopted SQM is that it relies on subjective input data. On the other hand, the physically-based models emphasize the effects of topography, by assuming steady-state hydrologic conditions and slope-parallel flow within the soil cover. A further drawback of the physically-based models is that they strongly rely on soil hydrologic and geotechnical parameters which are commonly difficult (and expensive) to quantify over large areas.

KEY WORDS: Flowslides, Susceptibility map, Physically-based models, Statistical approach, Southern Apennines.

**RIASSUNTO**: ANDRIOLA P., CHIRICO G.B., DE FALCO M., DI CRESCENZO G. & SANTO A., *Confronto tra modelli fisicamente basati ed un metodo semiquantitativo per la valutazione della suscettibilità all'innesco di colate rapide di fango in depositi piroclastici*. (IT ISSN 0391-9838, 2009).

Nel presente lavoro sono stati applicati due modelli fisicamente basati (SHALSTAB e SINMAP) ed un approccio statistico per la valutazione della suscettibilità di colate rapide di fango in depositi piroclastici dei contesti carbonatici della Regione Campania (Sud Italia). I risultati ottenuti evidenziano i limiti e le potenzialità di questi strumenti nella individuazione delle aree suscettibili all'innesco di colate rapide.

L'approccio statistico si basa su un campione di 187 colate rapide, le cui caratteristiche geologiche e geomorfologiche salienti sono state implementate in un metodo semi-quantitativo (SQM). Quest'ultimo, pur essendo più cautelativo, in quanto ha mostrato settori ad alta suscettibilità moderatamente più estesi, risulta più preciso nel predire la posizione delle aree sorgenti delle frane.

I modelli fisicamente basati sono più efficaci nel rispondere al meglio alle caratteristiche morfologiche locali, come ad esempio canali e aree convergenti e sono meno precisi, invece, nel prevedere l'innesco delle frane sui versanti planari o divergenti.

Il limite principale dell'SQM è che esso si basa su dati di input soggettivi, mentre quello dei modelli fisicamente basati è che essi tendono ad amplificare l'effetto della topografia, dal momento che utilizzano uno schema idrologico semplificato di tipo stazionario. Inoltre, i modelli fisicamente basati utilizzano parametri idrologici e geotecnici che sono difficili da reperire e quantificare su area vasta.

TERMINI CHIAVE: Colate rapide di fango, Carte di suscettibilità, Modelli fisicamente basati, Appennino Meridionale.

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## INTRODUCTION

The landslides considered in the present study are generally characterized by flow mechanisms involving water-sediment mixtures (Johnson & Rodine, 1984). Following Guadagno & Revellino (2005), these phenomena may be named «debris avalanche-debris flows». Nevertheless, according to Cascini & *alii* (2003) and Olivares & Picarelli (2006), the term «flowslides» (Hungr & *alii*, 2001) was used in this work.

This type of phenomena frequently occurs on the carbonatic ridges of Campania (Southern Italy), where they caused significant damage and casualties in the past. Flowslides usually originate within the pyroclastic or volcaniclastic soil mantle derived from the Somma-Vesuvius and Campi Flegrei volcanic systems, and result in severe risk conditions threatening 208 municipalities (Migale & Milone, 1998) (fig. 1).

Effective methodologies for identifying the areas most prone to triggering of shallow landslides are needed to design risk scenarios. Existing methods for evaluating the susceptibility to landslides can be grouped in two categories (Aleotti & Chowdhury, 1999): i) methods based on euristic-geomorphological approaches (Canuti & *alii*, 1985; Anbalagan, 1992); ii) methods based on deterministic (e.g. physically/process-based models) or statistical approaches (Van Westen, 1993; Carrara & *alii*, 1995; Iovine & *alii*, 2003).

In this paper, two well-known physically-based models, i.e. SHALSTAB (Montgomery & Dietrich, 1994) and SINMAP (Pack & *alii*, 1998), and a statistical-semiquantitative method are compared with respect to their effectiveness in assessing the susceptibility of potential flowslides source areas. Differences and limitations of the adopted methodologies are discussed based on data from a common test site, located in the Bracigliano municipality in Campania (fig. 1).

## THE PHYSICALLY-BASED MODELS

### *SHALSTAB*

SHALSTAB (SHAllow Landslide STABility model - Montgomery & Dietrich, 1994) is a distributed model that

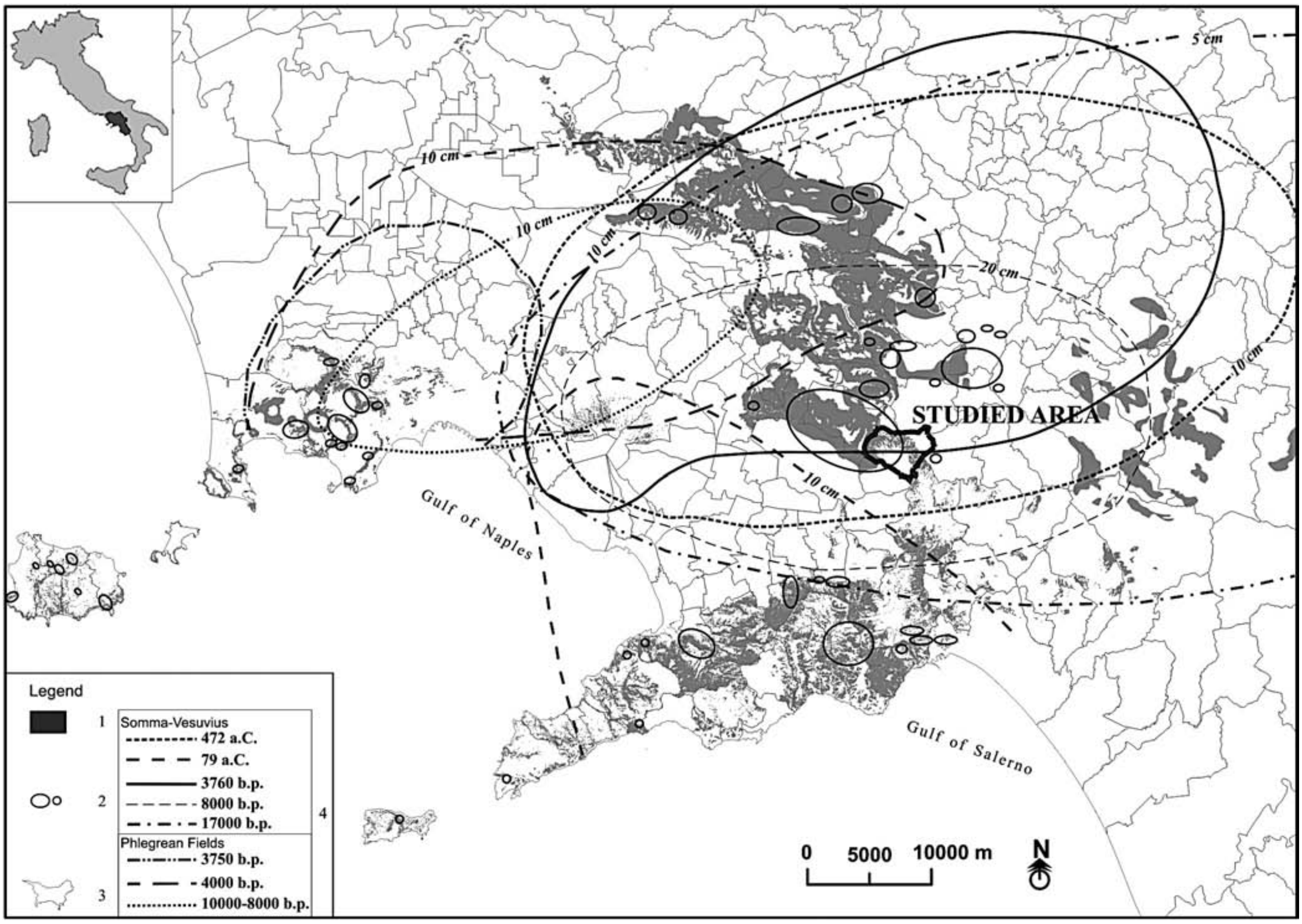



FIG. 1 - Flowslide prone sectors in Campania (after Picarelli & *alii*, 2008), and isopachs of the main pyroclastic fall deposits (after Rolandi & *alii*, 2000). The border of study area is shown with a bold line. Key: 1) potential sources of flowslides; 2) flowslide or group of flowslides; 3) boundary of municipalities; 4) pyroclastic air-fall deposits originated by Somma-Vesuvius and Phlegrean Fields.

couples an infinite-slope stability model (fig. 2a) with a steady-state hydrological model (fig. 2b). SHALSTAB is implemented as an extension of ArcView GIS, and uses a digital terrain analysis tool to quantify the basic terrain input data, including slope angle and contributing area.

The steady-state hydrological model was used to map the spatial variability of a wetness index, given by the ratio of the saturated depth ($h$) of the soil cover to the total soil depth ($z$). The wetness index is a function of the slope angle ($\tan\theta$) and of the specific contributing area, expressed by the ratio of the contributing area ($a$) to the corresponding contour length ($b$) subtending $a$ (fig. 2b). Figure 2c illustrates the relationship between wetness index ($h/z$) and slope angle ($\tan\theta$), for an angle of internal friction of 45° and a bulk density ratio of 1.6.

The infinite-slope stability model provides an assessment of the susceptibility to flowslide in terms of potential source areas, while it does not provide any prediction of other related phenomena, such as propagation and deposition of the mobilized material. Each location can be plotted in the parametric plane ($\tan\theta$, $h/z$) (fig. 2c), or in the parametric plane ($\tan\theta$, $a/b$), to identify its susceptibility to landslide triggering. The locations in which stable conditions were never identified, even in case of dry soil, were classified as «unconditionally unstable». These locations generally corresponded to sites with very-steep slope angles and rock outcrops. Conversely, the locations in which unstable conditions never occured, even in case of saturated soil, were classified as «unconditionally stable». These locations corresponded to areas with slope angles less than 20°, as illustrated in fig. 2c. In the remaining locations, the landslide susceptibility index was expressed as the upper value of the ratio between i) the effective rainfall ($q$) to ii) the soil cover transmissivity ($T$) for which unstable conditions were verified, according to the following relation:

$$\frac{q}{T} = \frac{sen\theta}{(a/b)}\left[\frac{c'}{\rho_w g z \cos^2\theta \tan\varphi'} + \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\varphi'}\right)\right] \quad (1)$$

where $c'$ is the effective soil cohesion, $\rho_s$ is the soil bulk density, $\rho_w$ is the water density, and $\phi'$ is the effective soil friction angle. Table 1 summarises the default stability classes used in SHALSTAB (after Montgomery & Dietrich, 1994).

TABLE 1 - Stability classes used in SHALSTAB (after Montgomery & Dietrich, 1994)

| Classification | log q/T (1/m) |
|---|---|
| I | Chron. Unstable |
| II | log q/T < –3,1 |
| III | –3,1 ≤ log q/T < –2,8 |
| IV | –2,8 ≤ log q/T < –2,5 |
| V | –2,5 ≤ log q/T < –2,2 |
| VI | log q/T ≥ –2,2 |
| VII | Stable |

*SINMAP*

SINMAP (Stability INdex MAPping - Pack & *alii*, 1998) employs a modelling framework similar to SHALSTAB, i.e. coupling an infinite-slope stability model (fig. 3a) with a steady-state hydrological model. The differences between SINMAP and SHALSTAB can be summarised as follows:

– the two models employ different algorithms for computing the slope angle and the contributing area;
– SINMAP accounts for uncertainty in soil hydrological and geotechnical parameters through uniform probability-distributions, according to expected or measured uncertainty in model parameters.

The factor of safety can be expressed as follows:

$$FS = \frac{C + \cos\theta\left[1 - \min\left(\frac{R}{T}\frac{a_s}{sen\theta};1\right)\cdot r\right]\cdot\tan\varphi'}{sen\theta} \quad (2)$$

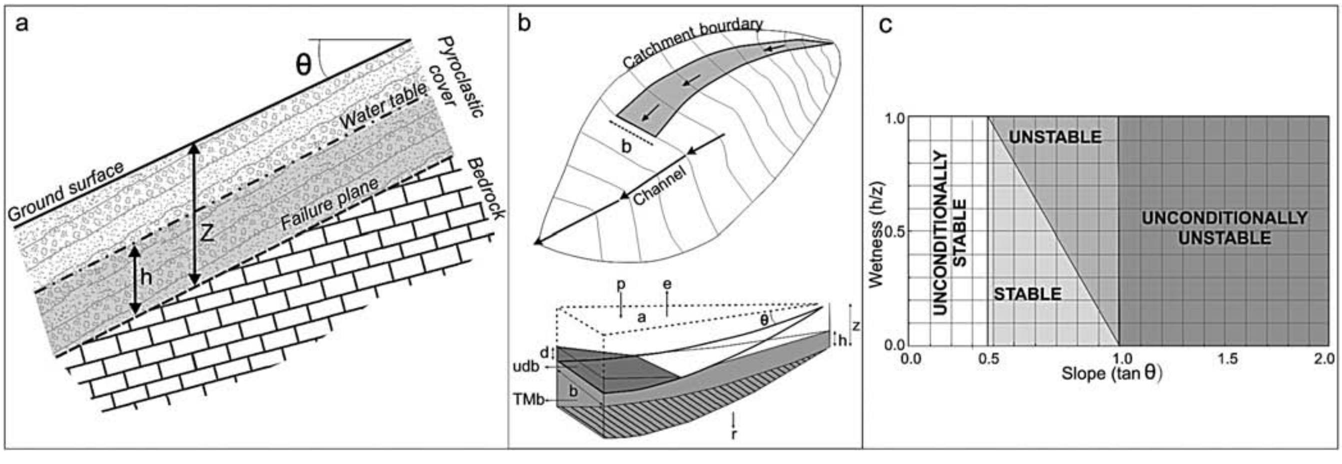



FIG. 2 - SHALSTAB conceptual model components (after Montgomery & Dietrich, 1994). Key: a) infinite-slope conceptual scheme; b) hydrological model ($p$, precipitation; $e$, evapotranspiration; $r$, deep drainage; $a$, drainage area; $h$, the height of the water table; $z$, soil thickness; $u$, mean subsurface flow velocity; $h$, water level of surface flow; $T$, transmissivity; $\theta$, slope angle; $M$, $\sin\theta$; $b$, contour length); c) definition of stability fields.

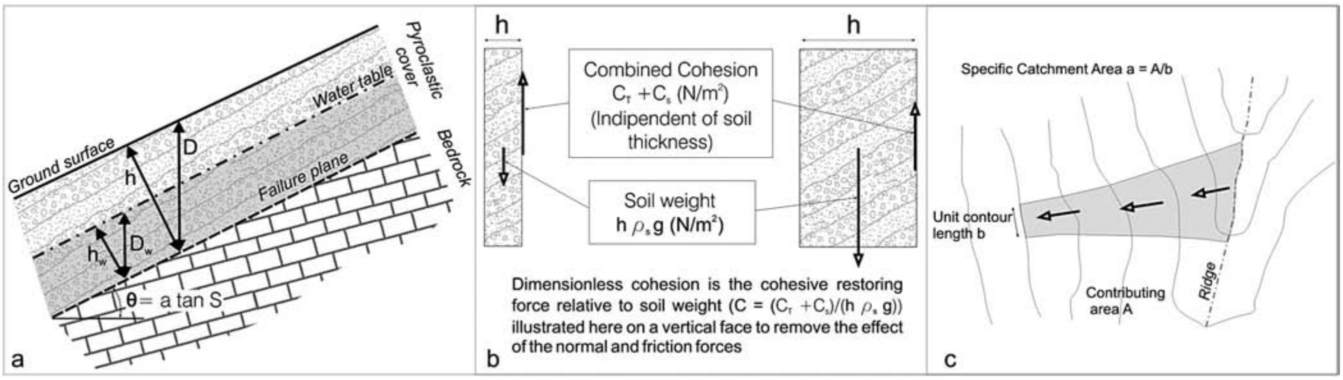



FIG. 3 - SINMAP conceptual model components. Key: a) infinite-slope conceptual scheme; b) illustration of the dimensionless cohesion factor concept; c) definition of specific catchment area (after Pack & *alii*, 1998).

where $C$ is the ratio between the soil cohesion and the weight of the soil cover per unit length (fig. 3b), $a_s$ is the specific contributing area, $\theta$ is the slope angle, $R$ is the effective rainfall, $T$ is the soil transmissivity, $\phi$' is the effective soil friction angle, and $r$ is the soil-water density ratio ($\rho_s/\rho_w$).

The dimensionless parameters $R/T$, $C$ and tan $\phi$' are treated as random variables with uniform probability-distributions, by assigning upper and lower limits to each of them.

SINMAP computes the susceptibility to flowslides source areas by means of a stability index (SI). Similarly to SHALSTAB, SINMAP does not provide any prediction of propagation or deposition. The safety factor was computed by considering the most conservative combinations of the above dimensionless parameters: it was assumed equal to the computed value if greater than one; otherwise, it was expressed as the probability that the safety factor was greater than 1. Table 2 summarises the default stability index classes used in SINMAP.

## THE STATISTICAL-SEMIQUANTITATIVE METHOD

A statistical-semiquantitative method (SQM) for characterizing flowslide source hazard was applied, following Di Crescenzo & *alii* (2008). The basis of this methodology is a sample of 187 flowslides, characterized by a travel distance exceeding 150 m, which occurred in Campania in the past century, whose locations and spatial extents were previously mapped by Di Crescenzo & Santo (2005a).

TABLE 2 - Stability index classifications adopted by SINMAP (Pack & *alii*, 1998). The classes Lower and Upper Threshold refer to two different ranges of the predicted SI, this representing the probability that a location is stable. The areas classified as Lower Threshold are characterised by a probability of being stable larger than 50%, while the areas classified as Upper Threshold are characterised by a probability of being stable smaller than 50%

| Classification | Stability Index (SI) |
|---|---|
| Stable | SI > 1,5 |
| Moderately Stable | 1,25 < SI ≤ 1,5 |
| Quasi-Stable | 1,0 < SI ≤ 1,25 |
| Lower Threshold | 0,5 < SI ≤ 1,0 |
| Upper Threshold | 0,0 < SI ≤ 0,5 |
| Defended | SI = 0,0 |

Slope angle and thickness of the soil cover at the potential source areas were assumed as factors mostly influencing the triggering conditions of the flowslides (De Vita & *alii*, 2006). The highest frequency of flowslides was found in the slope angle range 27°-55°. According to these statistics, a slope angle of 15° degree was considered as the lower limit below which the soil cover never reaches unstable conditions in the study area. No flowslides were observed above 55° as the soil cover is absent on such steep slopes (fig. 4a).

Most of the considered historical cases (97%) occurred where the thickness of the soil cover ranges between 0.5 and 4 m (fig. 4b). Moreover, 61% of the cases occurred where the thickness is between 0.5 and 2 m, while 35% in locations with thickness between 2 and 4 m. Finally, few cases were also recognized on thicker soil cover.

In addition to slope angle and soil cover thickness, the influence of rocky cliffs and man-made cuts on the generation of flowslides was already pointed out by several authors (Celico & Guadagno, 1998; Brancaccio & *alii*, 1999; Di Crescenzo & Santo, 1999; Guadagno & *alii*, 2003). In particular, in the same study area Di Crescenzo & Santo (2005a) observed that 45% of the source areas were located near man-made cuts and tracks, whilst 42% were in the vicinity of rocky cliffs (fig. 4c). In particular, over 100 source areas were less than 10 metres from artificial tracks and natural scarps (fig. 4f).

The occurrence of historical sources of flowslides is an indicator of susceptibility for the neighbouring areas, provided that these are characterised by similar geologic (thickness of pyroclastic cover) and geomorphologic (slope angle) conditions. Some areas are characterised by a cyclic occurrence of landslides with variable recurrence, in some cases of even few decades (Migale & Milone, 1998; Mele & Del Prete, 1999; de Riso & *alii*, 2004). In the study area, more than 88% of the mapped landslides occurred in places with evidence of ancient instability; 50% were near historical events, and 38% in the vicinity of landslide evidence, as identified from aerial photo-interpretation (fig. 4d).

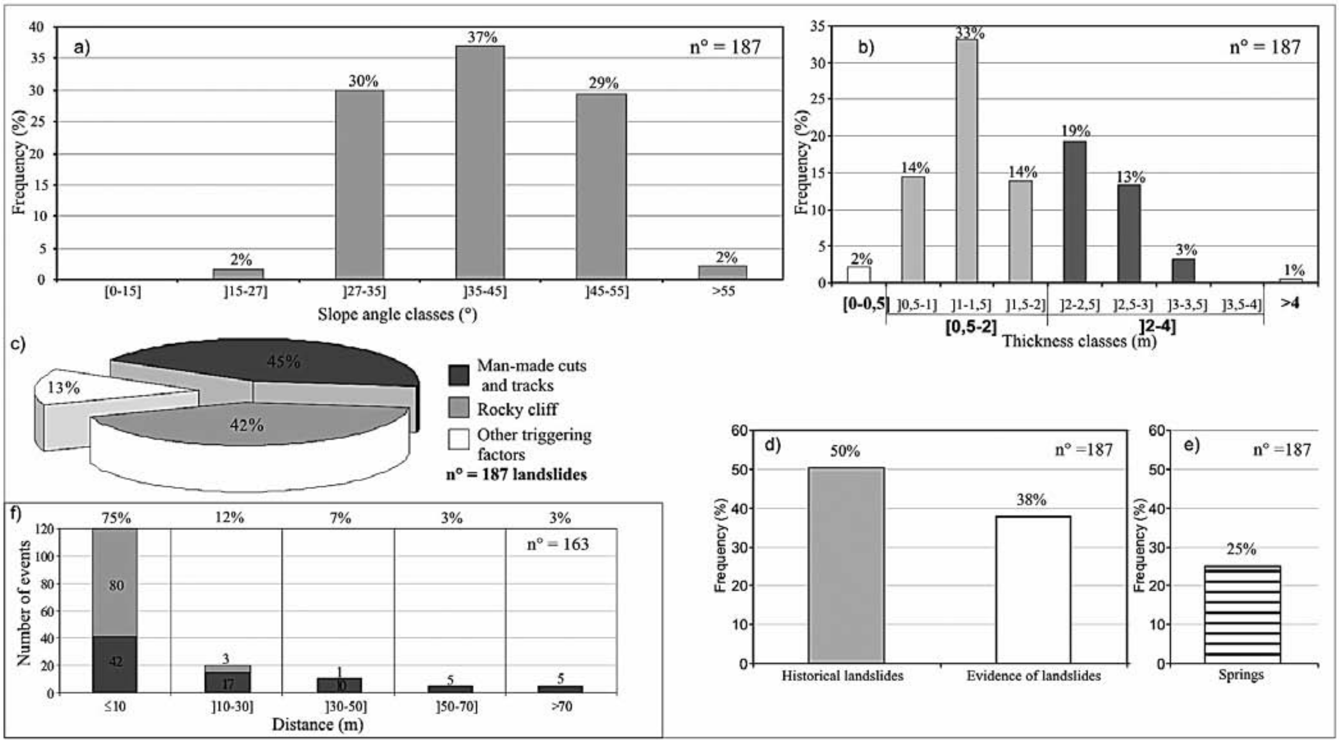



FIG. 4 - Frequency distribution of source areas against slope angle (a), pyroclastic cover thickness (b), man-made cuts, tracks and rocky cliffs (c), historical landslides or evidence of landslides (d), and springs (e). In (f), the distribution of the distance between the crown and man-made cuts, tracks and rocky cliffs is shown (note: the number of events is 163 because 24 flowslides are correlated to other triggering factors).

In many cases, ephemeral springs fed by the most fractured and karsified sectors of the limestone bedrock were observed in the source areas right after flowslides activation (Celico & Guadagno, 1998). During heavy rainfall, these springs can convey water into the soil cover, thus weakening the strength properties. Although it was not possible to check spring data for all the considered cases due to inaccessibility of the sites, 25% of them showed active springs in the vicinity of the source areas (fig. 4e).

For the present analysis, three different thematic maps representing the primary predisposing factors were compiled at 1:5000 scale (Di Crescenzo & *alii*, 2008): a cover map, a slope angle map, and a geomorphological map (including springs, tracks, pre-existing source areas, etc.). The three maps were digitised, geo-referenced, and raster transformed (cell size 5x5). Thickness of cover and slope angle are always measurable numerical quantities; the other factors were defined as «specific factors» and treated as binary variables, since they describe only the occurrence of a specific condition. Weight values were assigned to each parameter, ranging between 0 (minimum influence) and 4 (maximum influence), based on the relative class frequencies obtained from the collected data (tab. 3).

The three weighted thematic maps were overlain by means of a GIS application (ESRI ArcGis 9), and a susceptibility index value (I) was obtained for each cell by using the formula proposed by Di Crescenzo & *alii* (2008):

$$I = S^{(2T+1)} (C+Sp+Lme+Rc+L+1) \qquad (3)$$

TABLE 3 - Scores used for: a) the thickness of the pyroclastic cover (top); b) the acclivity (middle); c) specific factors (bottom)

| classes of acclivity S (°) | number of flowslides N | frequency f (%) | score |
|---|---|---|---|
| 0≤S<15 | 0 | 0 | 0,00 |
| 15≤S<27 | 3 | 2 | 0,06 |
| 27≤S<35 | 56 | 30 | 1,20 |
| 35≤S<45 | 69 | 37 | 1,48 |
| 45≤S<55 | 55 | 29 | 1,17 |
| S≥55 | 4 | 2 | 0,09 |

| classes of thickness T (m) | number of flowslides N | frequency f (%) | score |
|---|---|---|---|
| 0≤T<0,5 | 4 | 2,1 | 0,09 |
| 0,5≤T<2 | 115 | 61,5 | 2,46 |
| 2≤T<4 | 67 | 35,8 | 1,43 |
| T≥4 | 1 | 0,5 | 0,02 |

| Spring or springs area (Sp) | number of flowslides N | frequency f (%) | score |
|---|---|---|---|
| Rocky cliffs | 47 | 25,1 | 1,00 |
| Man-made cuts and tracks | 77 | 41,2 | 1,65 |
| Historical landslides | 47 | 25,1 | 1,01 |
| Evidence of landslides | 94 | 50,3 | 2,01 |

where:

– *I* is the susceptibility index;
– *S* is the average slope angle in the cell;
– *T* is the soil cover thickness assigned to the cell;
– *C* describes the occurrence of tracks and man-made cuts (a value of 1 is attributed to all cells within a distance of 10 metres from the observed tracks and man-made cuts);
– *Sp* describes the occurrence of springs in the cell;
– *Rc* describes the occurrence of rocky cliff (a value of 1 is attributed to all cells within a distance of 10 metres from the observed cliff);
– *L* describes the presence of documented historical landslides in the cell;
– *Lme* describes the presence of evidence of previous landslides in the cell.

The obtained values were normalised to the largest value, multiplied by 1000, and then subdivided into 5 different classes (tab. 4). The limiting values of the susceptibility index identifying each class were calibrated in order to maximise the ratio of the number of observed landslides in the highest classes to the extension of the total area falling in the same class. The calibration was performed on 774 flowslides occurred within 10 municipalities. In should be stressed that this set of flowslides does not include the 187 flowslides used for identifying the main geologic and geomorphologic factors, while it includes the flowslides occurred in the Bracigliano municipality.

TABLE 4 - Classes used to produce the susceptibility map (SQM)

| Classification | Susceptibility Index |
|---|---|
| Extremely low | $I<1$ |
| Low | $1\leq I<15$ |
| Medium | $15\leq I<35$ |
| High | $35\leq I<60$ |
| Very high | $I\geq 60$ |

## THE STUDY AREA

The investigated area covers 14.4 km$^2$ across the eastern slopes of the Pizzo d'Alvano Ridge, in the municipality of Bracigliano (fig. 5). It is characterized by high relief and steep slopes in stratified dolomite-carbonate bedrock; the area is widely covered by pyroclastic deposits, in places reworked and/or weathered, and deeply incised. According to Migale & Milone (1998), historical flowslides were recorded in this area since 1813, as shown in figure 6.

In recent time, the most significant event occurred on May, 5$^{th}$ 1998, when 32 hours of continuous rainfall, with an average intensity of 4 mm/h, hit the Massif of Pizzo d'Alvano (Chirico & *alii*, 2002). As a result, hundreds of flowslides were triggered on the slopes of the Massif. A volume of 150000 m$^3$ of soil was mobilized by the flowslides occurred in the Bracigliano municipality, according to the Commissary for the Hydrogeological Emergency in Campania Region (2005). Most of these flowslides travelled from the source areas into the channel network, causing six casualties and severe damage to roads and urban infrastructures. In addition, two minor

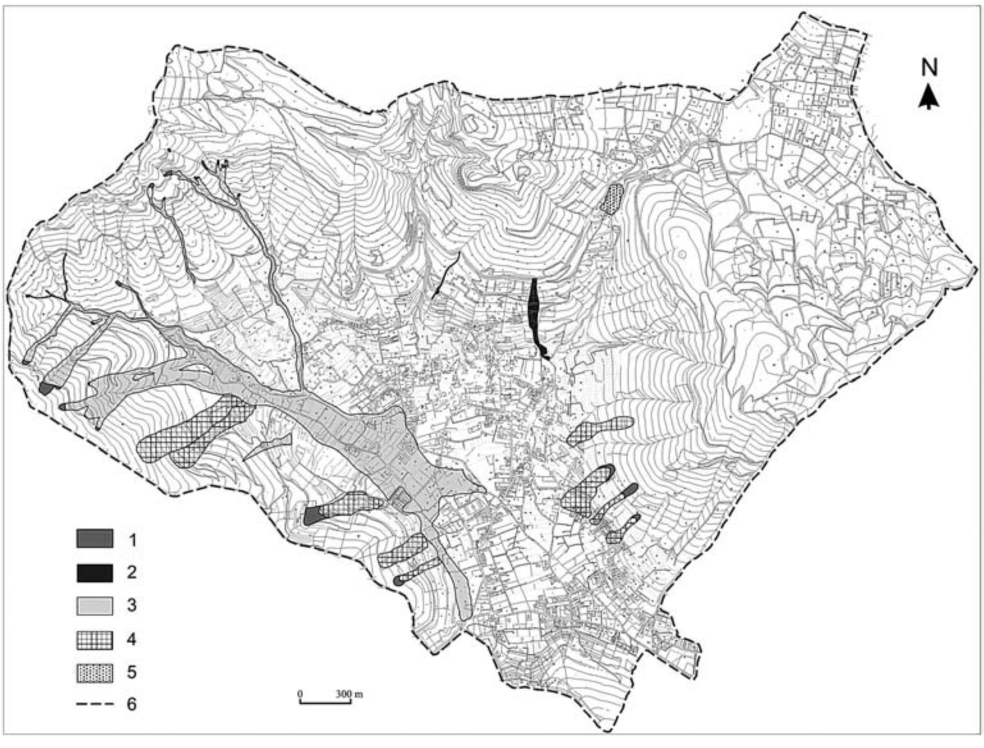



FIG. 5 - Landslide inventory map of the study area (for location, see fig. 1). Key: 1) source area; 2) flowslides occurred in 2004; 3) flowslides occurred in May 1998; 4) previous (undated) flowslides; 5) landslide in flysch deposits; 6) municipal boundary (modified from the thematic maps provided by the Commissary for the Hydrogeological Emergency in Campania Region, available at www.commissario2994.it).

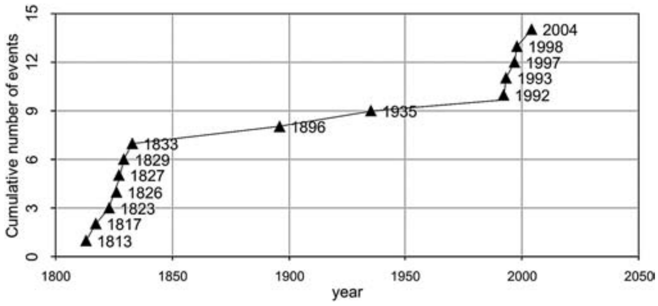



FIG. 6 - Distribution in time of the historical flowslides activations in the Bracigliano municipal area.

landslides occurred in the same area during a successive rainfall event, on December 26th, 2004.

In figure 5, other landslides that occurred in 1998 and 2004, and further phenomena (whose date of occurrence is unknown) are also mapped. The source area of each flowslide is also shown.

## INPUT DATA

A preliminary digital terrain analysis was performed in order to compute the topographic parameters needed for applying the physically-based models and the statistical approach. A grid DEM was derived from a contour elevation map, at a scale of 1:5000.

The hydrological and geotechnical parameters of the regolith were determined from available experimental datasets (e.g. Calcaterra & *alii*, 2004; 2005; Sorbino & *alii*, 2006). The adopted parameters are listed in tables 5 and 6. Soil depth was assessed from a detailed map provided by the Commissary for the Hydrogeological Emergency in Campania Region (2005). Nevertheless, as SHALSTAB Arcview extension allows to consider only a spatially-uniform soil depth, this parameter was set to 1 m, i.e. equal to the average depth of the failure planes observed at Pizzo d'Alvano Ridge (Cascini & *alii*, 2005).

TABLE 5 - Data input employed for the SHALSTAB software

| | |
|---|---|
| Friction Angle ($\phi$') | 34° |
| Soil Density ($\rho_s$) | 1400 kg/m$^3$ |
| Soil Depth (Z) | 1 m |
| Cohesion (c') | 2000 N/m$^2$ |

TABLE 6 - Data input employed for SINMAP software

| | |
|---|---|
| Gravity acceleration (g) | 9,81 m/s$^2$ |
| Soil Density ($\rho_s$) | 1400 kg/m$^3$ |
| Water Density ($\rho_w$) | 1000 kg/m$^3$ |
| T/R (lower bound) | 1440 m |
| T/R (upper bound) | 2880 m |
| $\phi$' (lower bound) | 32° |
| $\phi$' (upper bound) | 38° |
| *C* Dimensionless cohesion (lower bound) | 0 |
| *C* Dimensionless cohesion (upper bound) | 0,29 |

### *Identification and characterization of source areas*

Accurate geological and geomorphological surveys were conducted in the Bracigliano area to identify the location and the extent of the flowslide source areas (cartographic scale = 1:5000). A total of 29 source areas were identified, five of these related to events occurred before 1998 (fig. 5). Note that the latter five sources were excluded from the subsequent analysis, given the high uncertainty in the location of the actual source areas.

The total extent of the source areas related to the May 1998 and to the December 2004 events is about 11700 m$^2$. In these areas, detailed stratigrafic columns were surveyed and the most significant morphometric parameters were measured.

The frequency of source areas was assessed, relative to the maximum elevation of the crown scars (fig. 7a) and to the dominant slope angle class (fig. 7b). The results show that 84% of the slides occurred at elevations ranging from 600 to 1000 m a.s.l. Also, most of the first detachment areas occurred within the 30°-50° slope angle intervals, with highest frequencies between 35° and 45° (fig. 7b). Source areas were also classified according to the morphological features of the related hillslope (fig. 7c), such as: unchannelled hillslope sectors (V), channelled hillslope sectors (I), and hillslope sectors in the head basin (T). The occurrence of man-made cuts (s) or rocky cliffs (c) was also documented. About 63% of the source areas fell in unchannelled hillslope sectors, often associated with man-made cuts and rocky cliffs.

## RESULTS

The original number of susceptibility classes of SHALSTAB and SINMAP were reduced to five, as

TABLE 7 - Susceptibility classes adopted for the comparison of the results obtained with SINMAP, SHALSTAB, and SQM

| SQM | SINMAP | SHALSTAB |
|---|---|---|
| Extremely low | Stable | I |
| Low | Moderately Stable | II-III |
| Medium | Quasi-Stable | IV |
| High | Lower Threshold | V |
| Very high | Upper Threshold<br>Defended | VI-VII |

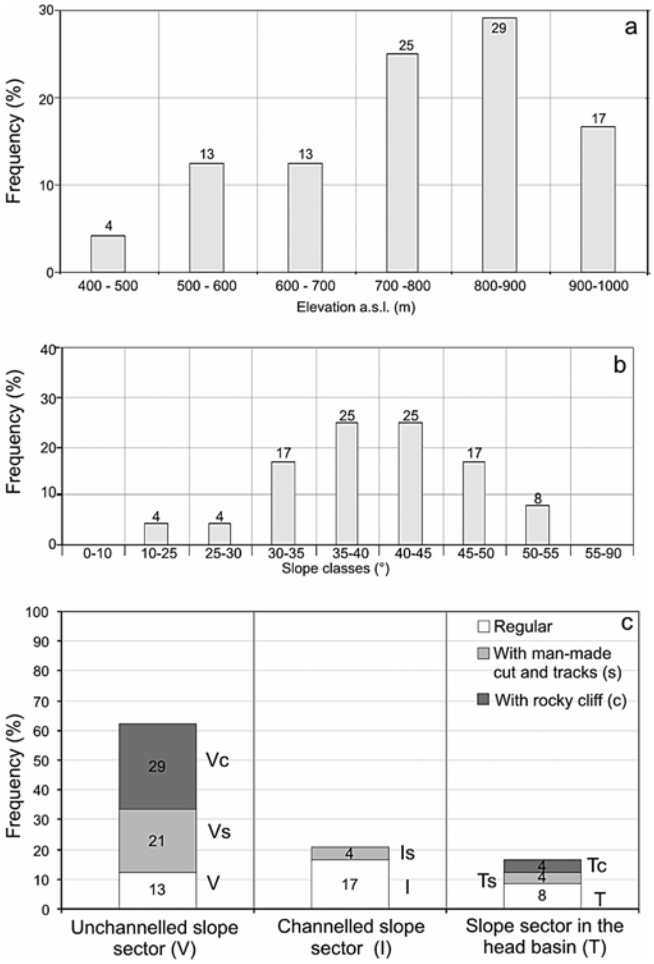



FIG. 7 - Relative frequency distributions of the source areas with respect to the a) crown altitude, b) slope angle, and c) hillslope morphological type.

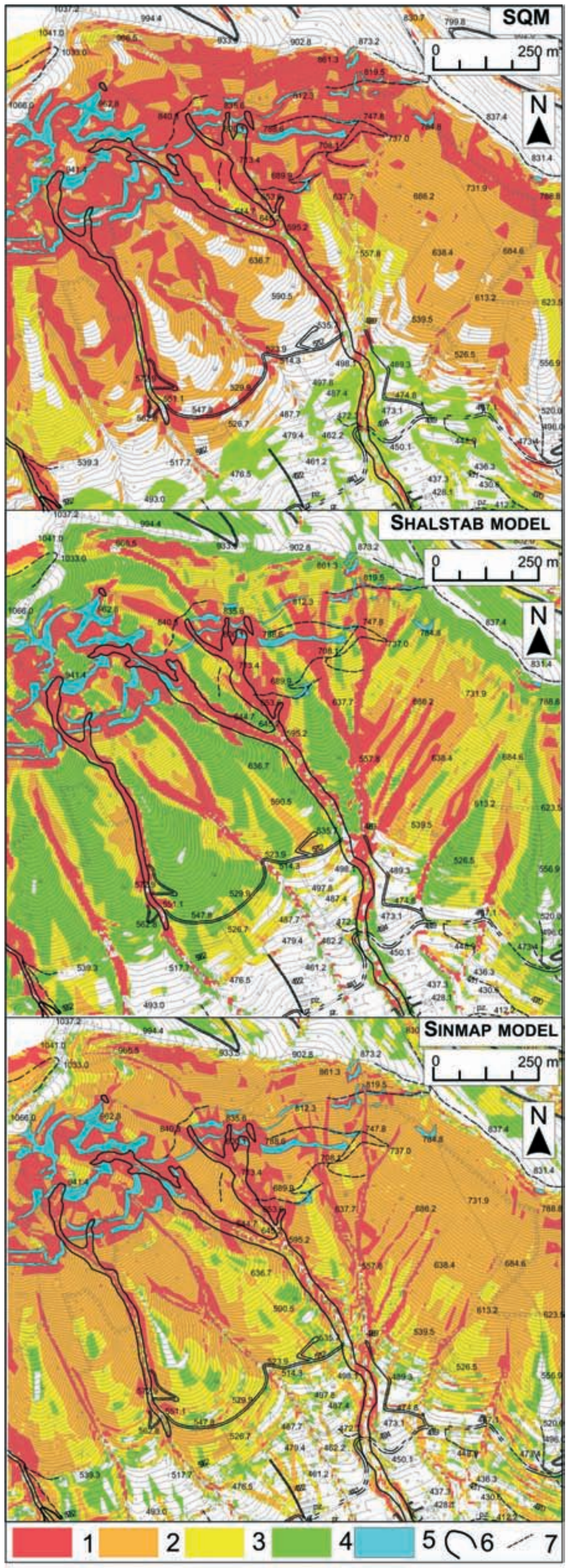



FIG. 8 - Exstracts from the susceptibility maps obtained by applying the SQM, SHALSTAB and SINMAP models (a-c, resp.). Key: 1) very-high, 2) high, 3) medium, 4) low susceptibility level; 5) rocky cliff; 6) flowslide; 7) man-made cut and track.

shown in table 7, to facilitate the comparison with the results obtained from the statistical approach. The resulting susceptibility maps are shown in figure 8. Frequency distributions of the susceptibility classes are provided in figure 9.

The extents of slope areas with null susceptibility obtained by using the three approaches are similar, being 48% for SHALSTAB, 42% for SINMAP and 51% for the SQM (fig. 9a). The extents of the areas with very-high susceptibility are 10% for SHALSTAB, 7% for SINMAP and 14% for the SQM, the latter being the most conservative. However, when excluding from the SHALSTAB and SINMAP statistics the rocky cliffs (which are not covered by soils), the results of the three methods are similar, with values of about 14%.

The distribution of the susceptibility classes within the historical source areas was also evaluated (fig. 9b). In this case, SHALSTAB and SINMAP classified only 36% of the historical sources within the very-high susceptibility class**,** while the SQM predicted 93%. As specified in the

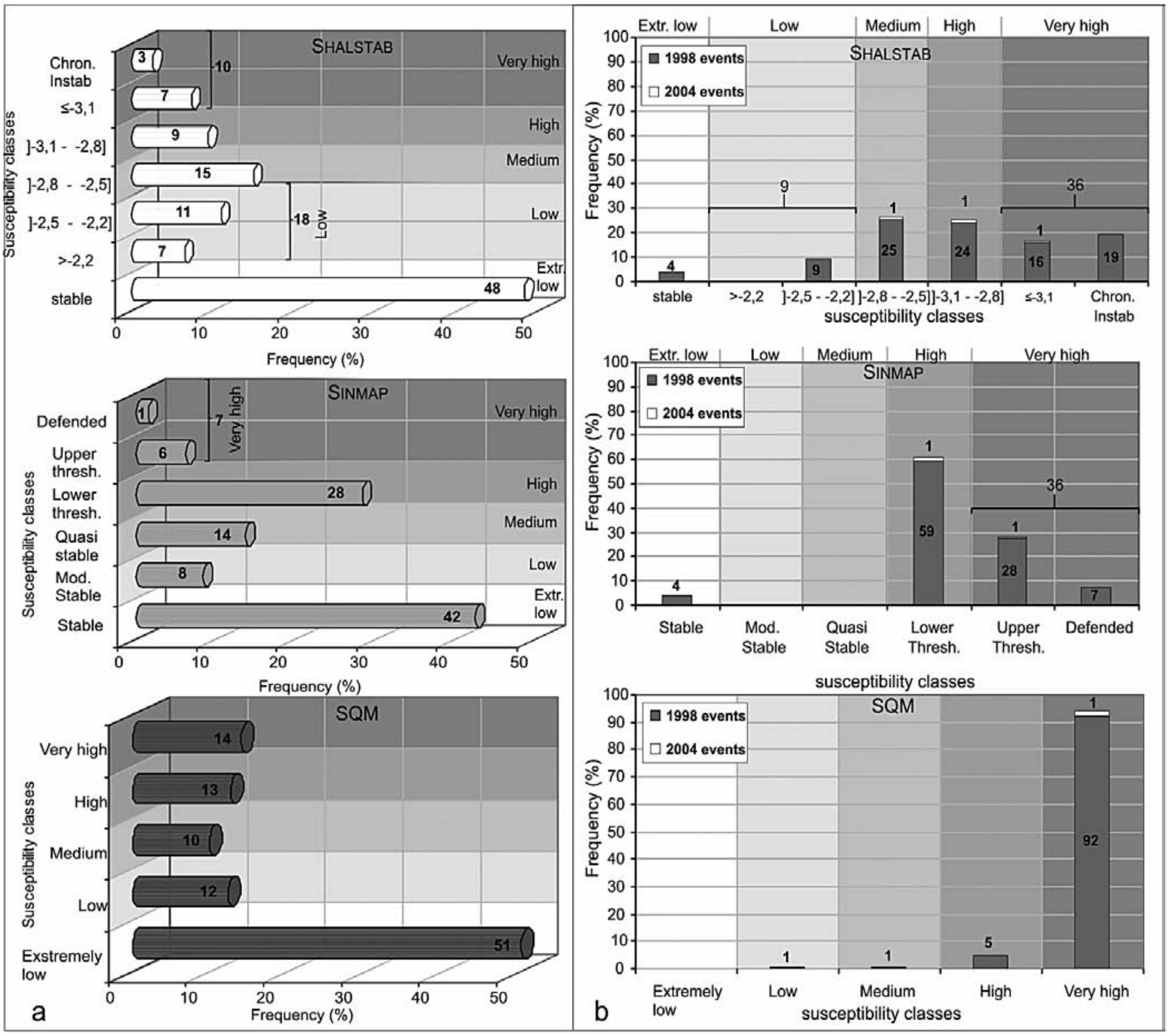



FIG. 9 - Distribution of the susceptibility classes. Key: a) on the municipal territory of Bracigliano (14,4 km$^2$); b) on the total extent of the source areas (11700 m$^2$).

figure caption, the figure 8 shows only a fraction of the overall study area and the percentages refer to the overall study area.

The distribution of the dominant susceptibility class among the 24 historical source areas were also evaluated (fig. 10), in order to take into account the largest susceptibility class in the source area. Physically-based models predicted less than 60% of the historical source areas within the very-high susceptibility class, while the SQM predicted 87%. A significant number of source areas were predicted by SHALSTAB in the low and in the average susceptibility classes.

Figure 11 illustrates the distribution of the susceptibility classes predicted for the source areas, classified according to the different morphological features, as defined in figure 7c. SHALSTAB provided better results for the sources located by the channels, predicting a very-high susceptibility level for 17% of the cases (fig. 11b). For the same subset of cases, SINMAP provided very similar results to the statistical approach. By the way, this latter method attributed a very-high susceptibility class to the majority of the source areas, particularly to those in non-channelled locations (V), even with natural or anthropogenetic morphological discontinu-

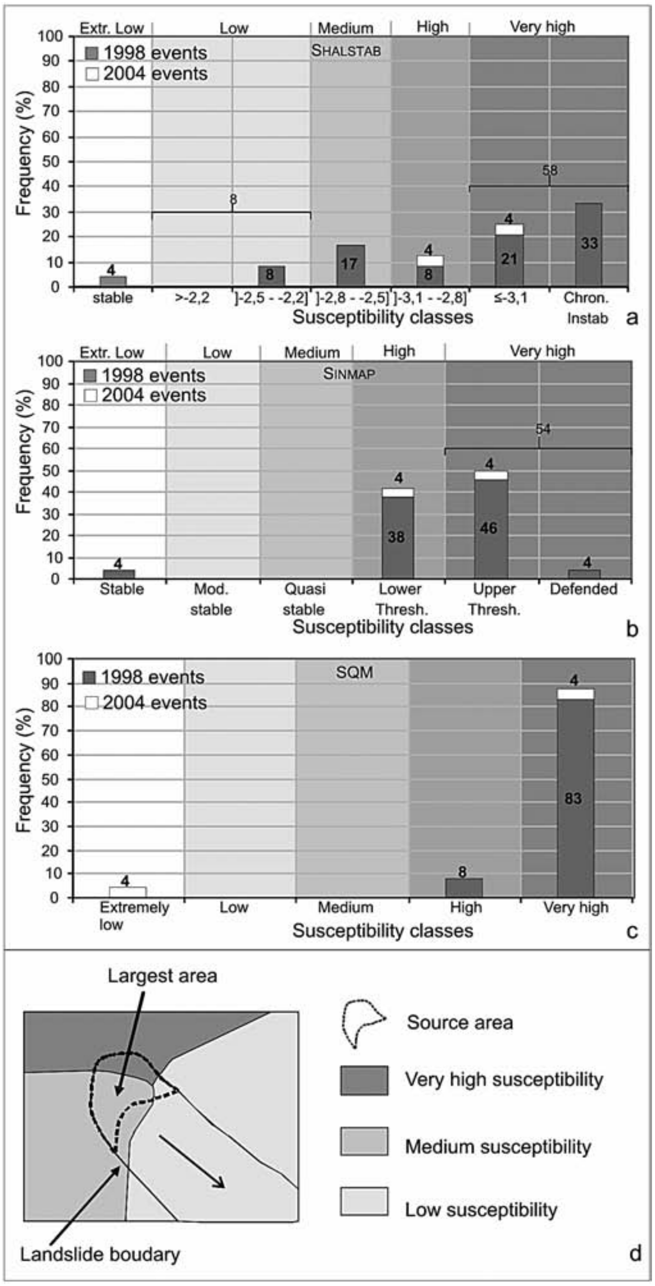



FIG. 10 - Distribution frequencies of the source areas (24) versus susceptibility classes.

ities (s). The frequencies predicted by the 3 methods are always consistent, except for the first two columns (V and VS): the physically-based models underestimate susceptibility on channel sidewalls, where landslides are still frequent.

The three different susceptibility maps were compared to evaluate the differences in the spatial distribution of the susceptibility classes (fig. 12). The comparison was performed by map overlay within a GIS environment. The areas classified with null susceptibility with both SINMAP and the SQM cover the 34% of the total area, while the areas classified with null susceptibility with both SHALSTAB and SQM cover 39% of the total area (fig. 12a). A similar analysis for the areas classified with very-high susceptibility, but restricted to the source areas, provides percentage of 23% (SHALSTAB/SINMAP) and 33% (SHALSTAB/SQM and SINMAP/SQM) (fig. 12b).

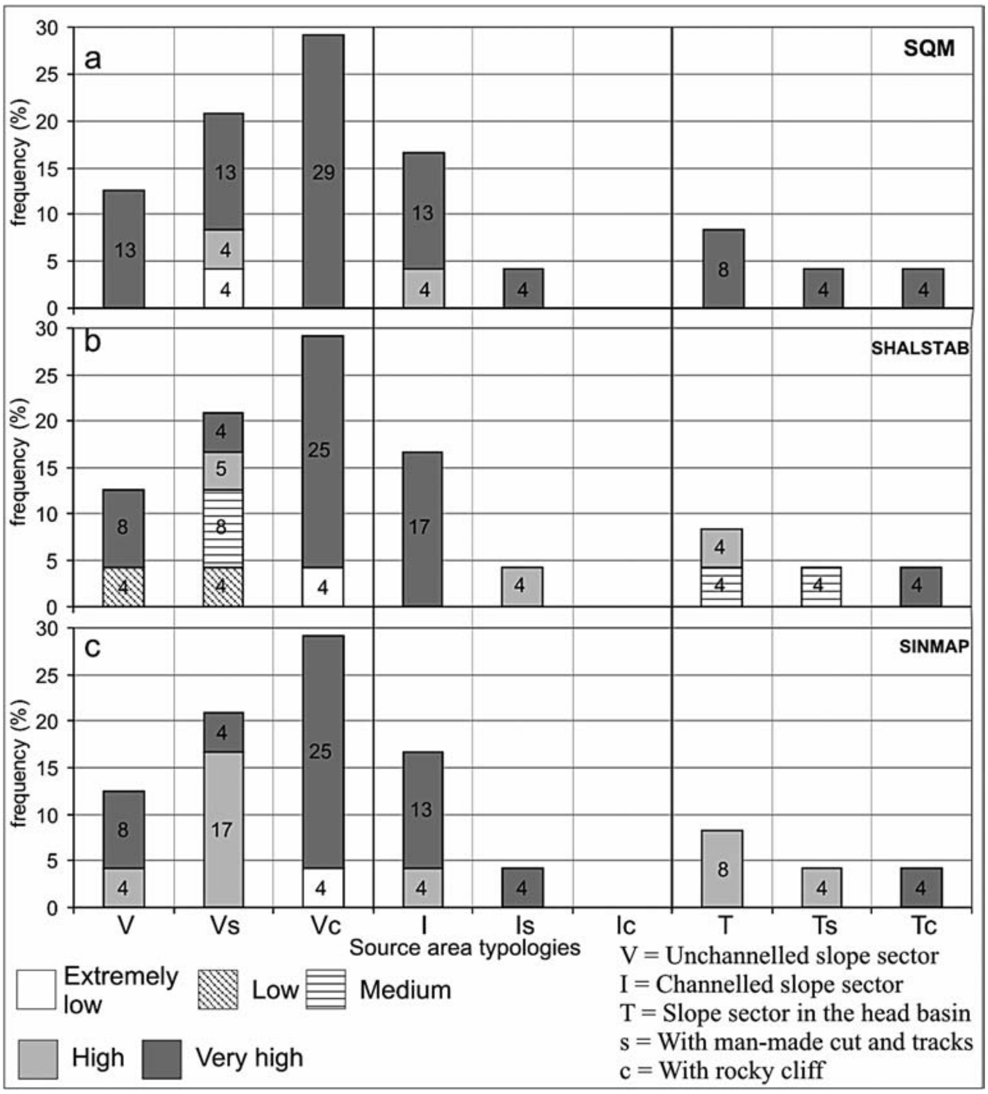
A visual comparison of the results obtained with SHALSTAB and SQM is provided by figure 13 for a large portion of the investigated area. The red colour shows the areas classified with very-high susceptibility by both models. A similar map (not shown here) was obtained by comparing the results obtained with SINMAP to SQM. From this latter comparison it can be assessed that the physically-based models predict high level of susceptibility in the channels, but underestimate susceptibility on channel sidewalls, where landslides are still frequent (see area «A» in figure 13). Finally, the physically-based models indicate areas with high level of susceptibility close to the channels at the hillslope foot, where the slope angle is too gentle for a landslide to be triggered (area B in figure 13); on the other hand, they do not classify at very-high susceptibility the sectors of «side slopes» characterized by high slope angles and by natural discontinuities or road cuts, even though, according to Guadagno & *alii* (2003), these factors are known to exert a primary influence on landslide triggering (cf. area C in figure 13).

## CONCLUSIONS

A comparison of the results obtained by applying a statistical-semiquantitative method (SQM) and two well-known physically-based models (SHALSTAB and SINMAP) for predicting flowslides susceptibility showed that the first method is the most accurate in classifying the locations of historical sources at very-high level of susceptibility. The same method, however, also indicated the largest area as having a high susceptibility. The physically-based models provided similar results in classifying the areas with high level of susceptibility along the channels, and in classifying areas with low level of susceptibility along the convex areas, at the foothills and in flat areas. Nevertheless, these models were not able to identify areas with high level of susceptibility along small channel lines or along planar hillslopes. They were very sensitive to topographic factors, but did not account for geomorphologic features commonly considered significant in determining the hydrological conditions that lead to landslide triggering. On the other hand, it should be stressed that the SQM is site-specific, and cannot be applied to other regions without a prior calibration based on local flowslides data. SQM also strongly relies on subjective evaluation of some key factors.

It is believed that a proper combination of the applied methods may provide a comprehensive evaluation of flowslide source susceptibility, which can be effective for planning risk mitigation strategies.

FIG. 11 - Frequency of the source areas versus source area types obtained with the SQM, SHALSTAB and SINMAP methods.



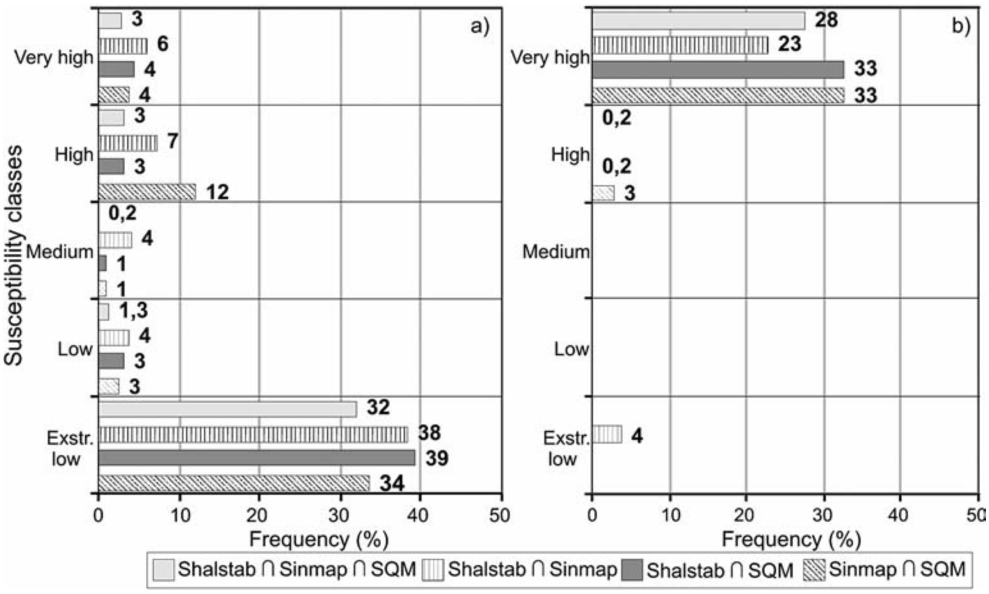




FIG. 12 - Comparative analysis of the methods by intersection operations on the basis of the distribution of the susceptibility classes in the territory of Bracigliano (a), and the total extent of the source areas (b).

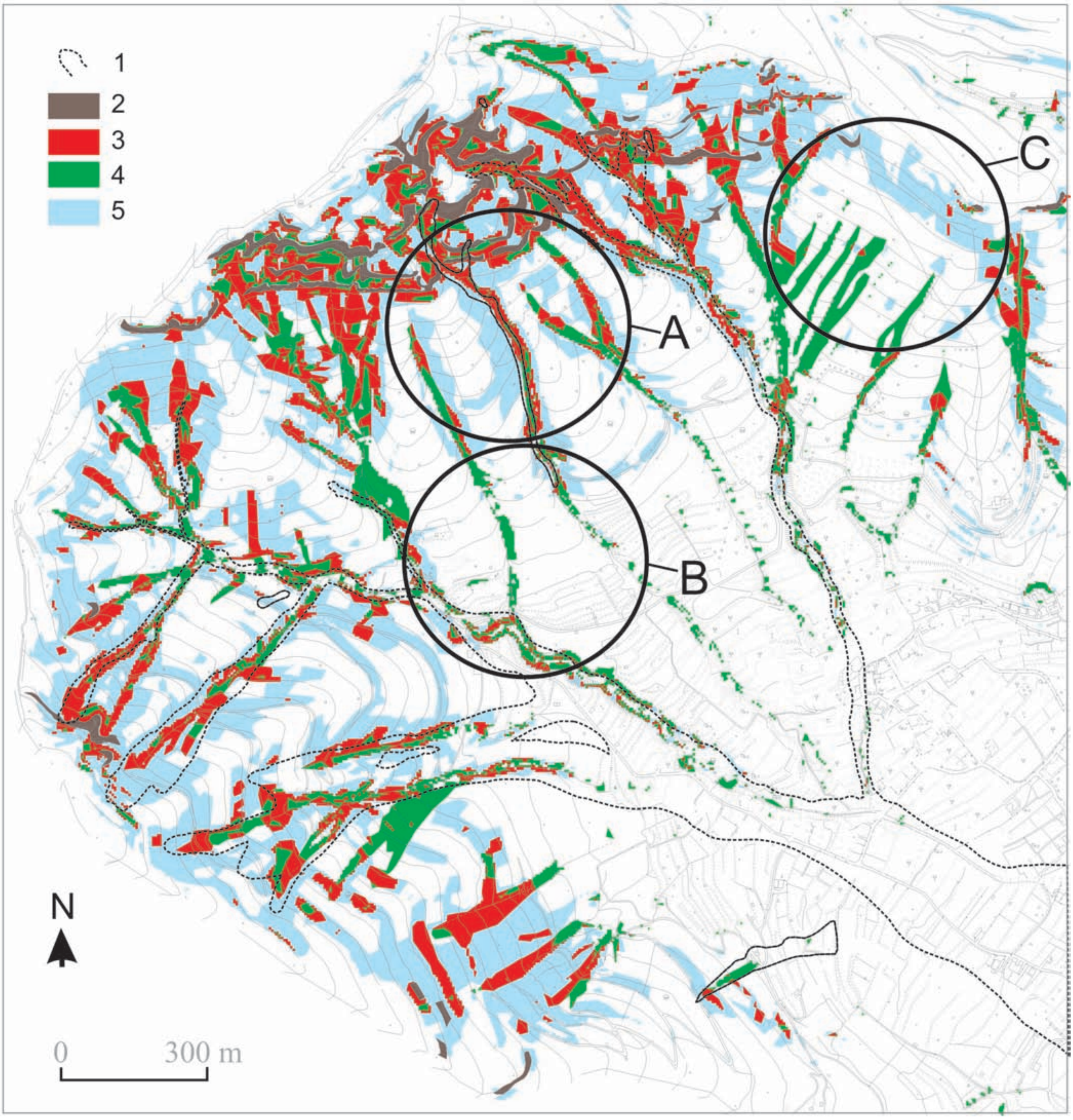



FIG. 13 - Very-high susceptibility distribution derived from SQM and SHALSTAB model. Key: 1) flowslide limit; 2) rocky cliff; 3) SQM and SHALSTAB; 4) SHALSTAB; 5) SQM. In the areas A, B and C, the most important dif-ferences obtained with the two methods are evident.

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