GIS database for the assessment of debris flow hazard in two areas of the Campania region (southern Italy)

M. Bisson(1), G. Cosimi(2), M. Favalli(1), F. M. Leoni(2), F. Mazzarini(1)
M. T. Pareschi(1)(*), R. Santacroce(2), S. Sgrò(2), R. Sulpizio(1)
and G. Zanchetta(2)

(1) *Istituto di Geoscienze e Georisorse del CNR - Via S. Maria 53, I-56100 Pisa, Italy*
(2) *Dipartimento di Scienze della Terra, Università di Pisa - Via S. Maria 53, I-56100 Pisa, Italy*

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Summary. — With the aim to support debris flow risk assessment and management in southern Campania a Geographic Information System (GIS) was implemented for two selected areas. The GIS provides the some basic themes useful for delineating debris flow hazard. They encompass geological and geomorphological maps as well as morphometric parameters like slope distribution, basin shape, drainage network, order of the stream or drainage density. Based on these data preliminary hazard proneness was discussed. A set of ortophotograms (AIMA) allows the assessment of the exposed values. The GIS is continuously updated and in the next future a more detailed zonation will be available.

PACS 91.40.-k – Volcanology.
PACS 91.40.Ft – Eruptions.
PACS 83.80.Nb – Geological materials: Earth, magma, ice, rocks, etc.

1. – Introduction

Steep hill-slopes are suitable areas for the formation of several kinds of mass wasting, representing a serious hazard for the people living at the hill-slope feet. In these areas, the development of hazard maps is a prerequisite for producing mitigation plans in supporting public administrations and Civil Protection decisions. Mountainous areas near explosive volcanoes are particularly hazardous, owing to the potential sudden remobilization of volcaniclastic deposits by heavy and/or prolonged rain, forming mud and debris flows. Although pronounced during, and enhanced following explosive eruptions, debris flow hazards must be considered a permanent feature of circumvolcanic areas [1].

(*) E-mail: pareschi@dst.unipi.it

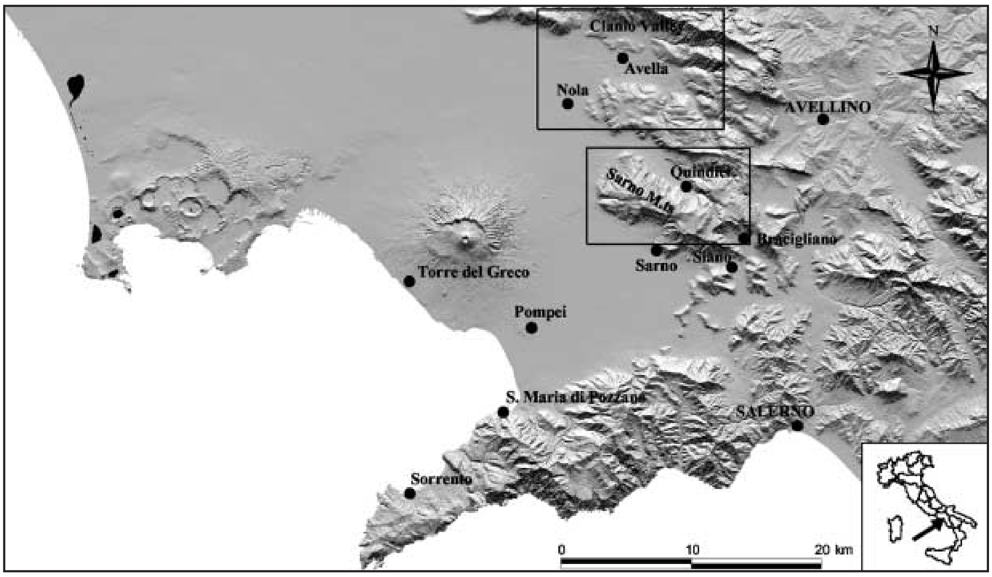

Fig. 1. – Shaded relief representation of a DEM obtained from topographic maps (Istituto Geografico Militare) at 1:25000 scale. Rectangle A: Clanio Valley; rectangle B) Sarno-Quindici-Bracigliano-Siano.

The debris flows formed by the remobilization of volcaniclastic material emplaced by Somma-Vesuvius and Phlegrean Field explosive eruptions (Campania, southern Italy) caused the recent disasters of Pozzano (January, 1997, 4 death), Sarno (May, 1998, 160 death), and Cervinara (December, 1999, 4 death). Historic data show that they were only the latest episode of catastrophic debris flow occurrence in the circumvesuvian area during the last three centuries [2].

It is well known that debris flow frequency is a function of hydroclimatic events [3, 4] geomorphologic settings, terrain variables and debris supply [5]. Although volcaniclastic debris flows have different trigger mechanism [6, 7] shallow landslides (soil slips) evolving into debris flows predominate long time after the eruptions when soil development stabilises the loose pyroclastic material [8-10]. Indeed, the debris flow of the southern Campania generally initiated as shallow landslide that rapidly transforms into flow [1, 11, 12].

In approaching hazard assessment a collection of detailed geological, geomorphologic, climatic and land-use data sets is need. Moreover, these data need to be integrated and stored in an accessible database.

The aim of this paper is the description of a database for the assessment of debris flow hazard in two selected sectors of Campania (fig. 1): the Clanio Valley ($\sim 161\ \text{km}^2$) and the Sarno-Quindici-Bracigliano-Siano (SQBS) area ($\sim 112\ \text{km}^2$). Both areas were affected by severe atmospheric disturbances in the recent past (*i.e.* 5-6 May, 1998), which triggered several debris flows, so that they are suitable areas for studying predisposing factors for debris flows formation. Data were obtained by direct fieldwork (performed at scale 1:10000) of our group integrated by stereo-pair analysis. Morphometric analyses were performed using a digital elevation model (DEM). The data collected are organised in a geographical information system (GIS). Moreover, a preliminary proposal for hazard zonation is briefly discussed. The database is available on a CD-ROM, under an e-mail

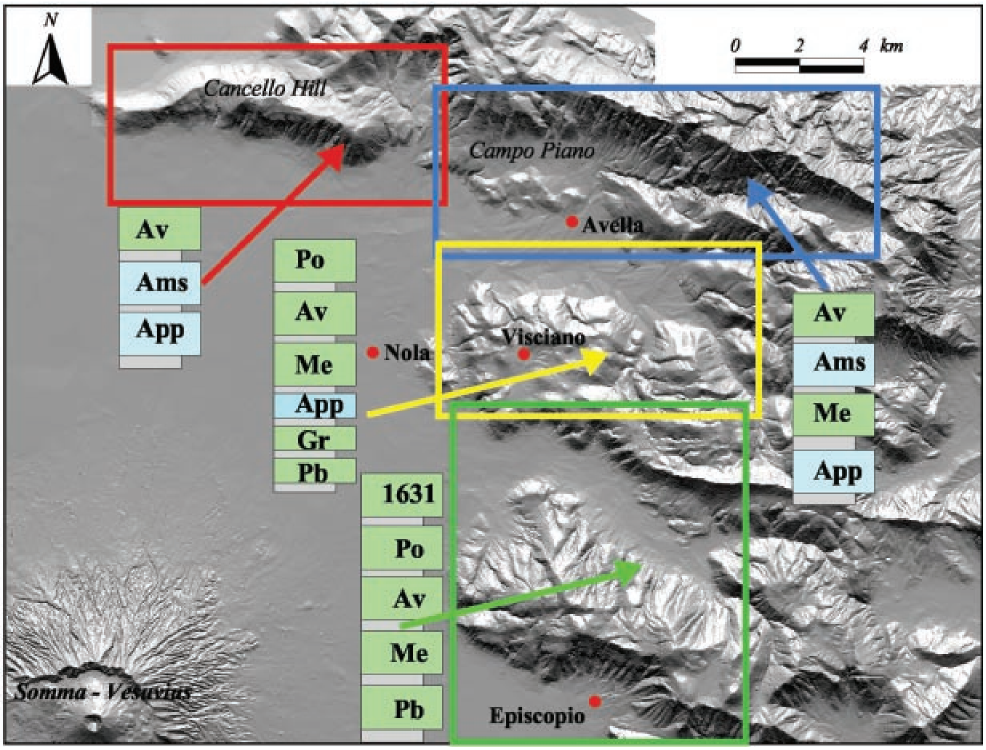

Fig. 2. – Successions of the pyroclastic fall deposits in different part of the studied area. Rectangles indicate the area of the main pyroclastic fall deposits recognizable in the hillslope soils. Stratigraphic columns schematically indicate the succession of pyroclastic fall deposits. The abbreviations refer to: 1631: deposits of the 1631 AD eruption (*e.g.*, Santacroce, 1987); Po: Pollena eruption, 472 AD (*e.g.*, Santacroce, 1987); Av: Avellino Pumice (ca. 3.8 ka, Andronico *et al.*, 1995); Ams: Agnano Mt. Spina eruption (ca. 4.1 ka, Di Vito *et al.*, 1999); Me: Mercato eruption (ca. 8 ka, Andronico *et al.*, 1995); App: Agnano Pomici Principali (ca. 10 ka, Di Vito *et al.*, 1999); Gr: Greenish eruption (ca. 15 ka, Cioni *et al.*, 2000); Pb: Basal Pumice (ca. 18 ka, Bertagnini *et al.*, 1998). Eruption colored in the stratigraphic column came from Phlegrean Field, whereas green colored came from Somma-Vesuvius volcano.

request to one of the authors (M. T. Pareschi). In the appendix the characteristic of the CD-ROM and the data enclosed are briefly illustrated.

2. – The study areas

In both Clanio Valley and in SQSB area (fig. 1, 2) the relieves are formed by Meso-Cainozoic carbonate rocks. They are covered by volcaniclastic material emplaced in the last thousands of years by the explosive activity of both Somma-Vesuvius and Phlegrean Fields [13, 14]. Detailed stratigraphy of Quaternary deposits is extensively discussed elsewhere [1,13-17] as well as the ages, stratigraphy and chemistry of the volcanic deposits cropping out in this area [18-22]. Field evidence and historical data indicate that debris flows occur frequently in these areas.

In particular, during the May 5-6, 1998 hundreds of shallow landslides occurred in these areas, generating debris flows that caused damages and casualties especially in the SQSB area [1,12,14]. The triggering of these debris flows is related to the infiltration of meteoric water that partially saturated the volcaniclastic soil. The total rainfall of May 5-6 (100–180 mm), although below the maximum recorded annual values, was seasonally exceptional. In fact, 2-day continuous rainfall in spring has a recurrence period of more than 100 years. Moreover, before May 1998, nine consecutive rainy days characterised by 2 days of maximum rainfall at the end of the sequence had never been recorded [23,24].

3. – Available data

The available data, whatever their nature and source, are georeferenced in the same cartographic system (UTM_ED 50-zone 33) and are organised in a Geographical Information System (GIS). The software used to implement this GIS is ArcView (version 3.x). The data of GIS are divided in two different groups (raster and vector). The raster data are constituted by images of different origins:

1) digital IGM maps at scales 1:25000, 1:50000, 1:100000, 1:250000. They represent a cartographic base where the various informative layers (buildings, roads, idrography, countour line, toponymy, etc.) can be visualised individually because memorised in different bit.

2) Landsat 5 RGB satellite images with a 30 m step. They refer to the last 10 years and can provide land use information.

3) AIMA ortophotos. They are 256 grey level images with a 1 m resolution on the ground.

4) Digital Elevaton Model (DEM) with a 10 m step from which it is possible to obtain several morphometric information (*e.g.*, slope, concavity).

The vector data are represented by graphic files (point, line, polygon features) that can be questioned, because linked to alphanumerical table where additional information are memorised (*i.e.* area of basin, river length, etc.). The vector themes are organised in five main layers: i) anthropic information (provincial administrative boundaries, borough administrative boundaries, towns, railway lines, roads, toponymy); ii) orography layers (contour lines and spot heights); iii) geologic layers (fault, geological units, strata attitude, thickness of volcaniclastic cover, etc.); iv) geomorphologic layers (alluvial fans, landslide, quarry, scarp, etc.), and v) hydrograph (drainage boundary, drainage network, etc.).

Regarding debris flows initiation some data are further discussed below, together with their characteristics. Because debris flows generations is a relatively frequent event in these areas and since there is a continuously effort in producing more detailed DEM to support morphometric analysis, the GIS is continuously updated.

3·1. *The digital elevation model (DEM).* – From the spot heights and contour lines (spacing contour lines 25 m; original data were available in digital vector format) of the IGM (Italian Geographic Army Institute) at 1:25000 maps, a Triangular Irregular Network (TIN) was constructed, approximating the surface of the study area by a network of triangular plane facets. The algorithm used is a variation of Delauny's method [14,25, 26]. From the TIN a DEM (Digital Elevation Model, 10 m resolution) was derived. The estimate errors of the digital cartography furnished by IGM are: i) for the spot heights ± 2 m in x-y and ± 2 m in z; ii) for the contour lines the error in z is ± 6 m in the 70% of the contour length (± 8 in the 100%). The available DEM actually covers large part of the southern Campanian Plain, including the volcanic apparatus of Phlegrean Fields

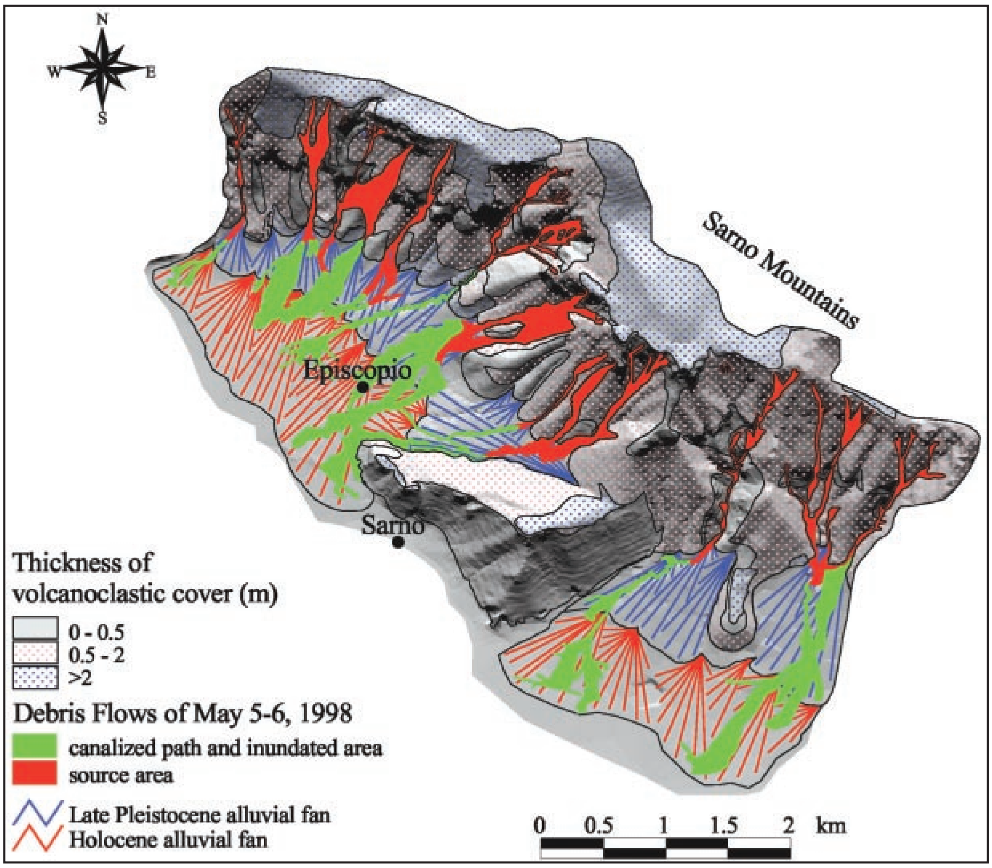

Fig. 3. – Schematic geologic and geomorphologic map of the Sarno-Lavorate area. The base is a DEM with two 2 m step.

and Somma-Vesuvius, the Penisola Sorrentina, the Mounts of Sarno and the Clanio Valley (fig. 1). For testing the quality of the morphometric data obtained from this DEM the aerial photographs of a recent flight (8 May 1998, Italian National Airforce, scale approximately 1:13000) were used to derive a more detailed DEM in an area of about 10 km^2 centred on the village of Episcopio (close to Sarno, fig. 3). From the aerial photographs a digital map with contour lines 5 m spaced was produced and, following the procedure discussed before, a new DEM was computed with 2 m step. The most important characteristics of the basins (basin shape, main maximum slope paths, including the main channel, average slope, etc.) are quite similar in the two DEMs. For instance, the basin area differences in the two DEMs are lower than 5%. Such an occurrence allows us to be confident about the reliability of the DEM based on the 1:25000 data, at a medium large scale for morphological analysis.

3˙2. *Geological, geomorphological and soil thickness maps*. – The geological, geomorphological and soil thickness maps are the basic tools for any preliminary approach to debris flow hazard assessment. In the GIS these maps are available in raster format.

3˙2.1. Geological and geomorphological maps. The bedrock geology is quite homogeneous in the whole study area comprising mostly carbonate rock. The Geological map mainly refers to the quaternary deposits with special emphasis to the alluvial fans and their state of activity. Indeed, the alluvial fans are natural archives that record the debris flow occurrences in their catchments. Furthermore, alluvial fan surfaces represent the potentially flooded areas. Usually, in the considered region, debris flow motion does not overcome the distal edge of the alluvial fans. For both Clanio Valley and Sarno Mts, 1:25000 geological maps are based on a field survey at scale 1:10000.

In the geomorphological map recent soil failure (scar and scarp), debris flow runout, and depositional lobes are mapped as well as older debris flows. In particular the typology and activity of alluvial fans ware investigated in detail.

3˙2.2. Soil thickness map. The thickness of the volcaniclastic soil cover was also considered. This represents an important data to assess the material potentially available to fail. Thickness measurements were obtained with direct measurement in outcrop, at the scarp of the landslide and using a manual sounding rod where outcrops are not available. In areas characterized by high soil thickness (> 2 m) stratigraphic data were obtained using a mechanical sounding rod coupled with a *AF s*hallow core system [16]. Punctual data were extrapolated with field survey control and grouped into 4 classes (0–0.5 m; 0.5–2 m; 2–5 m; > 5 m). These classes, of course, give a broad picture of soil thickness because local lateral variability of soil thickness can occur. However, it is interesting to note how debris flows commonly occur on hillslopes with soil thickness less than 2 m, this is a common occurrence also in other geological and geomorphological settings [10, 27]. Field survey shows how in the studied areas characterised by higher soil thickness only deeper rotational landslides occurred, and they did not evolve in debris flows. This probably depends on the amount of water necessary to saturate the soil thickness. It is really difficult to obtain condition in which high soil thickness became fully saturated and then creating high pore pressure, a condition for debris flow formation. High soil thickness may have the capacity to drain water in deeper part of the soil, and failure occurs before to reach critical condition to form debris flow.

3˙2.3. Hillslope characteristics. Hillslope characteristic like slope gradient and concavity can affect the debris flows susceptibility in several ways. For instance, it influences the direction and amount of surface runoff or subsurface drainage. As discussed in Pareschi *et al.* [1,14,15] small, funnel-shape drainage basins are the most prone areas for the occurrence of debris flows in the studied areas. For instance during the atmospheric disturbance of 5-6 May 1998 90% debris flows in the SQSB area and 96% in Clanio Valley initiated within these morphological elements. In addition, the definition of topographic concavities is an important clue, being the preferential area where shallow landslides developed [27-29]. So the detailed analysis of these small drainage basins is fundamental in hillslope zonation. To trace drainage divide, an appropriate algorithm was developed and the results were checked by visual inspection on the DEM and topographic map to avoid any incongruence.

Every drainage basin was numbered, represented in vectorial format with related table where is stored alpha-numerical information as: area of the basin, mean slope; drainage density, etc.

3˙2.4. Drainage network. The drainage network was computed automatically from the DEM. Calculated drainage network shows a good consistency compared with drainage network obtained from map at 1:25000, and field survey. In areas characterised by very

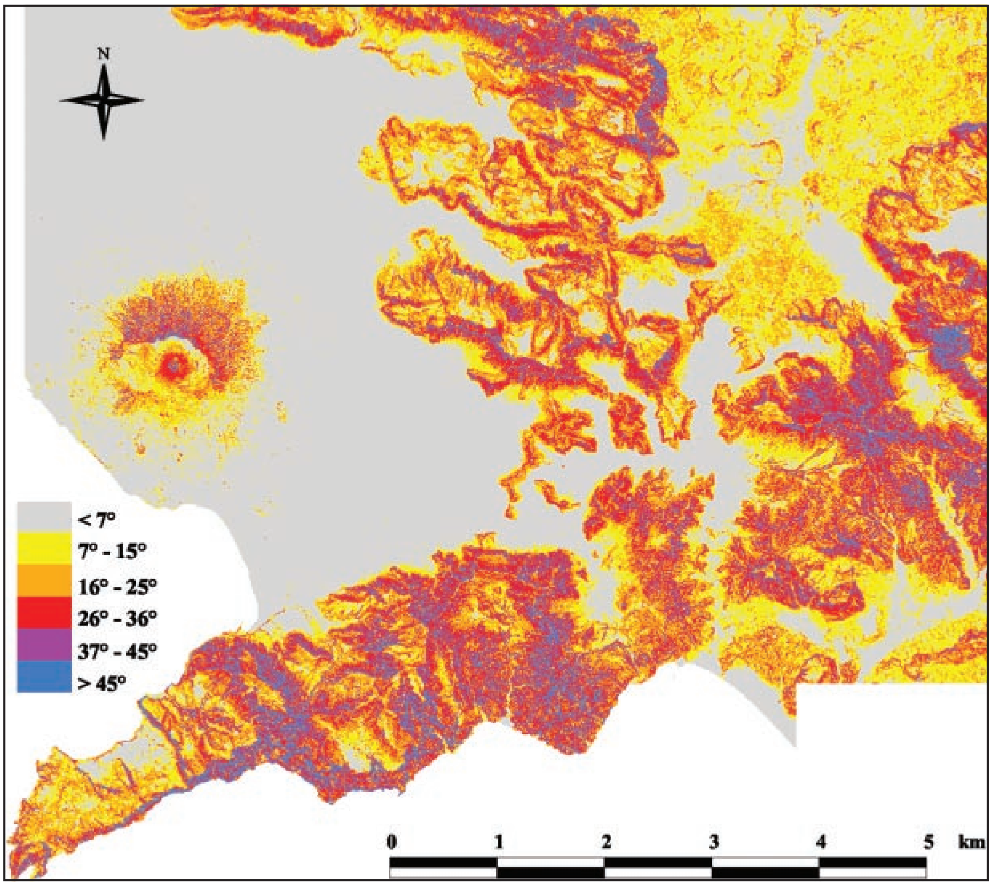

Fig. 4. – Slope map of the southern Campania derived automatically from the TIN obtained from the spot heights and contour line of the IGM 1:25000 maps.

low slope (less than 10°), the automated drainage network shows a lesser consistency. This is due to both a scarce availability of topographic data and the presence of several artificial channels that are not correctly identified by the algorithm that traced the synthetic drainage network.

3˙3. *Slope map*. – The slope map was obtained from the DEM, with 1° of resolution. The slope is an important parameter to define hazard susceptibility [27, 30]. World-wide data shows that slopes, in debris flow source areas, are usually comprised between 25° and 45° [4, 30, 31, 32]. In the Clanio Valley and SQSB [1, 14, 15, 33] soil slip/debris flow mostly initiated in slopes between 26° and 36°. In the Penisola di Sorrento (fig. 1) De Crescenzo and Santo [34] report slope for soil slip/debris flow occurrences slightly higher with slope ranging from 36° to 49°. Figure 4 shows the slope map of the southern Campania obtained by TIN, the area covers the same extension of fig. 1.

3˙4. *Basin-shape factor*. – In a recent paper Pareschi *et al.* [1] discussed the potentiality to use the shape of the basins (defined as the basin-shape factor), coupled with the relative mean slope, as the key parameter to define the debris flow hazard potential

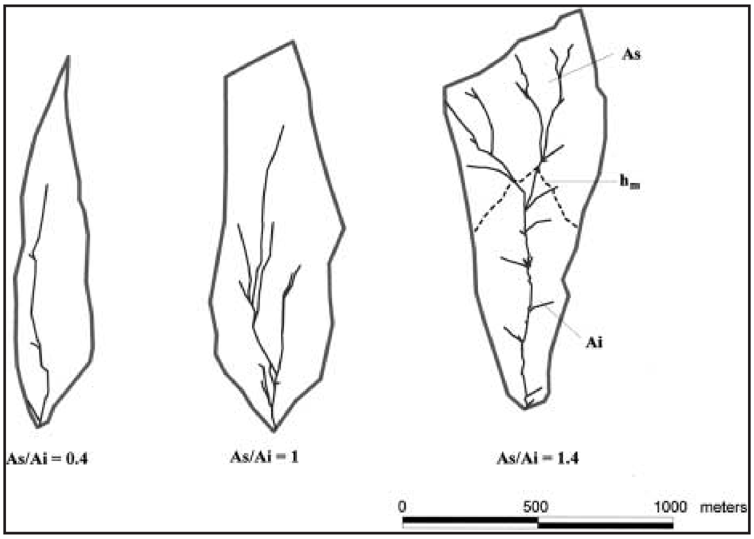

Fig. 5. – Some examples of basin shapes in Sarno-Quindici-Siano-Bracigliano region. The basin-shape factor is defined as ratio of the upper area of the basin (As) to lower area (Ai). The boundary between these two areas is at location of average elevation of basin.

of the small drainage basins (up to order 3). The approach has been extended and validated by comparison with field data (occurrence of debris flows) on about 450 basins ($\sim$ 62 km^2, $\sim$ 24% of the studied area) for the whole studied area. The basin shape factor (fig. 5) is defined as the ratio between the areas upper and lower respect to the mean height of the basin [1]. In the database, the shape factors of all the basins and their mean slope are available. This factor takes into account the relief energy and the increasing capability of the basin to collect up-slope rainwater routing it in the main stream. Instead, mean slope gives an idea of the critical slope to generate debris flows. High basin-shape factor increases the capability to collect rainwater, whereas a higher mean slope indicates the increase of critical areas exposed to slope failure. Both factors enhance the slurry mobility. Evaluating and coupling these morphometric data from the DEM allow to analyse easily and quickly hundreds of basins. This approach can be useful for a preliminary assessment of hazard potential in areas of southern Campania where few data are available. However, this approach is not able to give specific information on the extent of the areas prone to be disrupted in a drainage basin and then to address estimation of magnitude of potential event. This implies that, once identified a basin as potentially prone to be disrupted, other specific parameters need to be implemented (*e.g.*, soil thickness, hillslope, concavity, soil properties, etc.).

3·5. *Hillslope curvature*. – It is well documented that debris flows frequently initiate in topographic concavities, called hollows, filled with colluvial soils [29, 27, 28]. This morphological feature characterised the source area of several soil slip/debris flows in the studied areas. A detailed field survey can help in the identification of elementary concavities, especially in small areas of few km^2. More difficult and time-consuming is the case of working on wide and sometime remote areas. We propose here a simple and rapid method using the DEM. Using the Sobel operators [35] and the matrix of the

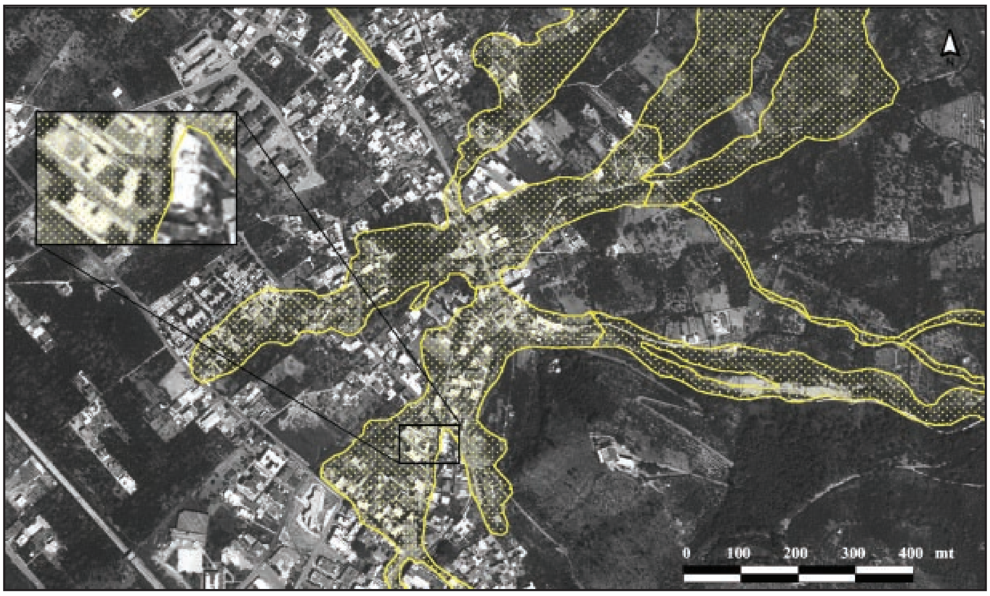

Fig. 6. – Sarno-Episcopio's AIMA Ortophoto. Green dotted area indicates the area flooded by the May 5, 1998 debris flows event.

height, the matrices of the second derivatives (in x, y and mix) have been obtained. The mean curvature has been obtained from the second derivatives, which correspond to the track of the Hessian matrix divided by two. The radius of curvature is ugual to the inverse of the mean of the two main curvatures. These data concern the topographic surface and cannot give specific information on soil-filled hollows, which have a more planar morphology than bedrock topography. Although this is a limit of the method, the limited thickness of soil involved in soil slip/debris flows and the size of the soil slip minimize the error that can arise from bedrock morphology and DEM resolution.

3˙6. *Remote-sensing analysis*. – Remote-sensed data together with field data and DEM have been used to produce thematic maps of land use and land cover in south-eastern part of Campania region. Remotely sensed data consist of Landsat 7 ETM (Enhanced Thematic Mapper), acquired during the 1999 Summer. Six bands of the scene (three in the visible and three in the infrared) have a 30×30 m pixel of resolution; and two (in the thermal range) have a 60×60 m spatial resolution step. The panchromatic band with a higher spatial resolution (15×15 m) is also available. Ground truth sites were surveyed by direct inspection or by stereo-pairs aerial photos analysis, and some land-use/cover types have been identified (*e.g.*, brush, crops, woods, urban type). Image processing techniques were applied to image data. No atmospheric corrections have been applied to the images since a uniform contribution has been assumed. Normalised Differentiation Vegetation Index (NDVI) and Tasselled Cap (TC) transformations [36,37] were performed to differentiate vegetation cover, soil moisture, soils and rocks, other materials. The Principal Component Transformation (PCT) was also achieved in order to reduce the data redundancy and better visualise the different surface types in the scene. The resulting images (NDVI, TC and PCT) were used to define areas (Region of Interest, ROI) corresponding to the main surface types occurring in the region, *i.e.*

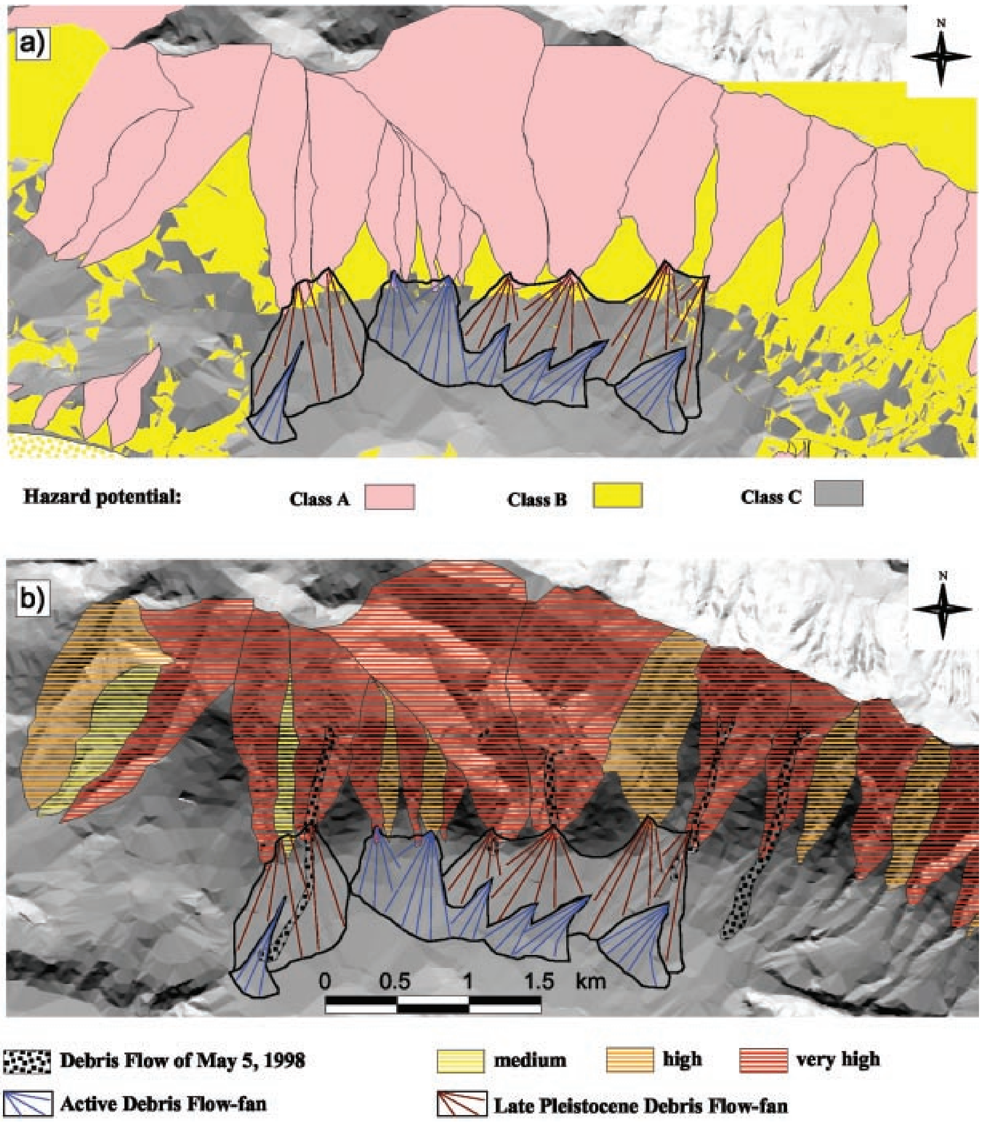

Fig. 7. – Examples of hazard potential zonation for a selected part of the Clanio Valley (a) using geological and geomorphological criteria. This classification is valid for the source area of debris flows. Class A: high; Class B: medium; C: low. In b) the areas within the class A are further divided using the basin-shape factor.

to identify "building classes" for the land cover and land use analysis. A supervised classification was then performed on original data by the Spectral Angle Mapper [38]. The classification resulted in a thematic map with colours representing different types of land use (agricultural, urban, woods, culture) and type of land cover.

3˙7. *AIMA ortophoto*. – To support hazard and risk assessment a set of AIMA ortophotos (Azienda di Stato per gli Interventi nel Mercato Agricolo, 1997-1999) can aid

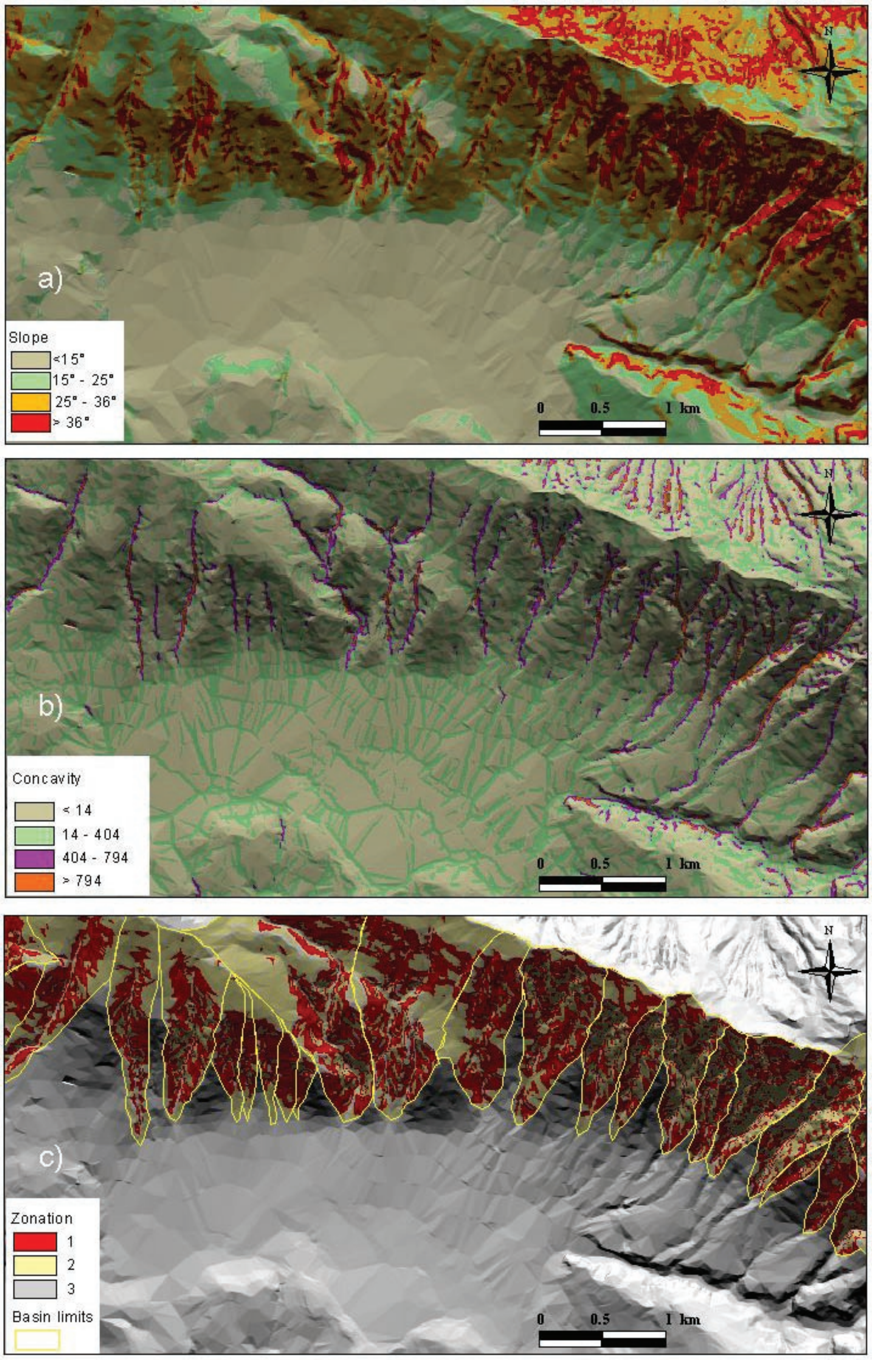

Fig. 8. – Example of hillslope zonation using slope (a) and hillslope concavity (b). From the intersection of the two maps a possible zonation is obtained (c): 1) high hazard potential; 2) medium hazard potential; 3) low hazard potential.

the evaluation of the exposed values. These images available for all the region have a ground resolution of 1 m. They allow to distinguish in detail the urbanised area and to make an assessment of exposed values. An example is shown in fig. 6 relative to Episcopio village where the different damages produced by 1998 debris flows were assessed.

4. – Preliminary proposal for hazard potential in the source areas of debris flows

Recently Pareschi *et al.* [1, 14, 15, 21] using data on the recent and historical debris flows occurrences and slope proposed hazard zonation (fig. 7a) as regard the Clanio Valley. They considered in zoning the potential source areas of debris flows: i) slope distribution; ii) occurrences of debris flows during May 5-6, 1998 or in the preceding years and/or occurrence of active alluvial fans with debris flows deposits at the mounth of the drainage basin; iii) order of drainage basins. Substratum geology and geotechnic characteristic of the volcaniclastic cover were considered to be uniform throughout the study area and were not included as variables for analysis. Combining these data they divided the area into three classes of hazard potential (fig. 7a): *Class A*: the class of higher hazard potential. It includes: i) the drainage basins where there is evidence of debris flows in the last years and/or debris flows deposits in the downstream alluvial fans; ii) the drainage basin (up to order 3) with mean distribution of slopes greater than 25°. *Class B*: this class includes the hillslope with slope $> 15°$, and not classified in Class A. *Class C*: this class includes all the areas that can be considered safe from the formation and runout of debris flows characterised by hillslopes lower than 15° (excluding areas classified in Classes A and B). Field data do not provide evidence of debris-flow formation in these areas. In the zone defined as major hazard potential (Class A) for the source area of debris flows a further detailing has been reached using the basin shape factor (fig. 7b) as defined by Pareschi *et al.* [1]. Within these areas a more detailed zonation is, however, possible using, for instance, slope and hillslope curvature (fig. 8a,b,c). Basing on the values of the slope and the concavities of the disrupted areas in the Clanio Valley and SQSB areas, it was possible to group together the critical values normalised respect to the percent of occurrence of soil slip. For instance, in the Clanio Valley (fig. 8a,b,c) 57 soil slip/debris flows initiated for the 77% on slopes between 26° and 36°, 21% in slope $> 36°$ and 2% in slope $< 26°$. The range of topography concavity are 62% between 15 and 404, 24% in concavities with values lower than 15 and 14% in concavities higher than 404. Giving a specific "weight" to the slope distribution and concavity of the debris flows occurrence it is possible to obtain different classes of disruption susceptibility. A preliminary example is shown in fig. 8a. Three different classes of susceptibility are there defined. Despite this approach need further improvement it make it possible to estimate the maximum volume of soil potentially involved in failure.

5. – Conclusions

The predisposed GIS allows a view on the main morphological and geological factors influencing debris flow development in the area West of Vesuvius. In addition, it provides a suitable geo-referenced framework (with information about past occurrences and characteristics of the area) where future information can be added. A zonation (1:25000 scale resolution) of the hazard susceptibility of the source areas and the potential flooding zones was performed. A rapid method to refine the hazard inside the area of major hazard potential based on shape of the drainage basin and slope was also

TABLE I. – *CD structure.*

Images

Name	Content	Color-depth	x-y coordinate first point top-left
Dem.tif	Digital Elevation Model	8 bit per pixel	x: 412523.42 y: 4539114.33
Slope Map.tif	Clanio Valley slope map	8 bit per pixel	x: 451351.13 y: 4541088.49
Geological Map.tif	Clanio Valley Geological map	8 bit per pixel	x: 449314.47 y: 4543564.61
Geomorphological Map.tif	Clanio Valley geormphological map	8 bit per pixel	x: 450821.72 y: 4542205.91
Episcopio slope.tif	Sarno-Episcopio-Bracigliano-Siano slope map	8 bit per pixel	x: 465767.14 y: 4522137.13
Cover's Map.tif	Volcaniclastic soil thickness of Clanio Valley	4 bit per pixel	x: 450494.42 y: 4540833.70
Potenzial hazard Map.tif	Hazard potential map of Calnio Valley	8 bit per pixel	x: 451111.54 y: 4540802.61
Slope Cover Map.tif	Intersection of soil cover map and slope for Clanio Valley	8 bit per pixel	x: 450366.70 y: 4541955.35

Vector

Name	Content	Features
Municipality Boundaries .shp	Municipality boundary of the Clanio Valley	polygon
Basins_Clanio.shp	Name, Area, Perimeter, Elongation Ratio(1), Mean Slope, Concavity, Drainage Density(1) Basin shape factor, Drainage Order(1) (Clanio Valley)	polygon
Basins_Sarno.shp	Name, Area, Perimeter, Mean Slope, Basin shape factor (Sarno-Quindici-Bracigliano-Siano)	polygon
Hydrography_Sarno.shp	Drainage network of Sarno-Quindici-Bracigliano-Siano (2)	line
Hydrography_Clanio. shp	Drainage network of Clanio Valley (2)	line

(1) The data refer to the areas where the cartography at scale 1:5000 is available.
(2) The two drainage networks partially overlap.

implemented. Within these areas further refinements are possibly useful to estimate the volume potentially involved in debris flows.

The GIS proposed does not take into account physical characteristic of soils involved in failure and hydrological conditions that are basic data for the implementation of slope stability model [39,40]. Future work should be addressed in improving the physical model starting from the data available or adequately integrated by new information.

Another important limitation of the data so far available arises from different scales of source data, namely field work, remote-sensing imagery and data obtained from morphometric analyses (from TIN and DEM). Obviously the merging of these data can produce some incongruence, however for preliminary analyses they are here considered quite consistent in particular because many themes are furnished at, and obtained from, the same scale (1:25000) and georeferenced respect to the same cartographic system. In the future a better data resolution and collection should be obtained from some selected basin which appears, according to preliminary zonation, more hazardous.

Appendix A.

CD Structure

The CD-ROM contains some selected products derived from the available GIS.

The data are organised in 2 directories: *images* (containing 8 file.tiff) and *vector* (containing 5 file.shp, table I). All data are georeferenced and the coordinate system used is U.T.M. 33_E.D.50. The images are thematic maps that can be used as support for visualising vector data. We present in the table the main characteristics of images and vector files.

* * *

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