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GIS and Volcanic Risk Management

M. T. PARESCHI, L. CAVARRA, M. FAVALLI, F. GIANNINI and A. MERIGGI
CSGSDA-CNR, via S. Maria 53, I-56100 Pisa, Italy

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Abstract. Volcanic catastrophes constitute a major problem in many developing and developed countries. In recent years population growth and the expansion of settlements and basic supply lines (e.g., water, gas, etc.) have greatly increased the impact of volcanic disasters. Correct land-use planning is fundamental in minimising both loss of life and damage to property. In this contribution Geographical Information Systems (GIS), linked with remote sensing technology and telecommunications/warning systems, have emerged as one of the most promising tools to support the decision-making process. Some GIS are presented for two volcanic areas in Italy, Mt. Etna and Vesuvius. GIS role in risk management is then discussed, keeping in mind the different volcanic scenarios of effusive and explosive phenomena. Mt. Etna system covers a large area (more than 1,000 km^2) potentially affected by effusive phenomena (lava flows) which cause damage to both houses and properties in general. No risk to life is expected. The time-scales of lava flows allow, at least in principle, modification of the lava path by the building of artificial barriers. Vesuvius shows typically an explosive behaviour. In the case of a medium size explosive eruption, 600,000 people would potentially have to be evacuated from an area of about 200 km^2 around the Volcano, since they are exposed to ruinous, very fast phenomena like pyroclastic surges and flows, lahars, ash fallout, etc. Ash fallout and floods/lahars are also expected in distal areas, between Vesuvius and Avellino, downwind of the volcano. GIS include digital elevation models, satellite images, volcanic hazard maps and vector data on natural and artificial features (energy supply lines, strategic buildings, roads, railways, etc.). The nature and the level of detail in the two data bases are different, on the basis of the different expected volcanic phenomena. The GIS have been planned: (a) for volcanic risk mitigation (hazard, value, vulnerability and risk map assessing), (b) to provide suitable tools during an impending crisis, (c) to provide a basis for emergency plans.

Key words: volcanic risk assessment, GIS, digital cartography, volcanic hazard, Vesuvius, Etna.

1. Introduction

Geographical Information Systems (GIS) are computer-based systems used to store and manipulate geographic information. They are designed to "support the capture, management, manipulation, analysis, modelling and display of spatially referenced data for the solution of complex planning and management problems" (Aranoff, 1989). The manipulation of data extends from the simple overlay of different thematic maps for the identification of areas with specific required conditions, to the more sophisticated use of mathematical operators or integrated numerical models for the prediction of the dynamics of natural phenomena. GIS technology, when applied to land use planning and natural resource management and protection, is a tool that can support scientific research and decision making, and serve as a surrogate laboratory for studying environmental processes (Burrough, 1989).

This contribution focuses on the major role GISs play in volcanic hazard and risk assessment/mitigation and their importance in the decision-making process.

Examples are presented and discussed for two Italian volcanic areas:

Mt. Etna (a large area – more than 1,000 km^2 – potentially interested, where effusive local phenomena are expected – lava flows – causing damage to houses and property in general)

Vesuvius (in the case of a medium size explosive eruption, 600,000 people have potentially to be evacuated from the proximal areas. This area is exposed to ruinous, very fast phenomena like pyroclastic surges and flows, lahars, etc. Ash fallout and floods/lahars are also expected at distal areas, between Vesuvius and Avellino, downwind of the volcano)

2. GIS Layers

The main thematic maps and spatial information necessary for a GIS devoted to volcanic risk management and mitigation are:

2.1. DIGITAL ELEVATION MODELS

DEMs are continuous raster layers in which data file values represent elevation. Alternative data organisations approximate terrain surfaces as a network of planar triangles (Triangulated Irregular Network: TIN), where vertexes are points of known elevation (Pareschi and Santacroce, 1993; Macedonio and Pareschi, 1991; Pareschi *et al*., 1999, in press; Favalli *et al.*, 1999, in press). A DEM is available for Mt. Etna (original scales of quoted points: 1 : 10,000), and Vesuvius (original scale 1 : 5,000 around the volcano, and 1 : 25,000 in the surrounding region).

The DEM of Mt. Etna (Figure 1(a)) was obtained by computing, on a regular grid, the elevations provided by the triangles of a “modified” Delaunay triangulation. There are 1,060,916 input points in an area of 1,800 km^2, centred on the volcano. The average density is: 1 point per 42 $\times$ 42 m area; with peaks of 1 point per 100 m^2 in the steepest regions (i.e., Valle del Bove). The number of triangles is 3,089,107, with an average area of 600 m^2 (Pareschi *et al*., 1998).

The DEM around Vesuvius (Figures 1(b–d)) covers an area of 48 $\times$ 50 km (1,987 km^2 without the sea). The boundaries of the domain are (Gauss–Boaga coordinates): 442,570–4,491,290 m (South-West corner) and 496,053–4,534,208 m (North-East corner). The input data of the cone comes from contour lines at a scale of 1 : 5,000. In this area (about 200 km^2), there are 629,348 points along contour lines and 13,033 isolated values; the average density is 1 point per 15 $\times$ 15 m. The DEM of the surrounding area has been derived from the IGM contour lines at a scale 1 : 25,000 (1,309,009 input points are organised along contour lines; another 18,250 are isolated points). The total number of triangles is 3,346,438.

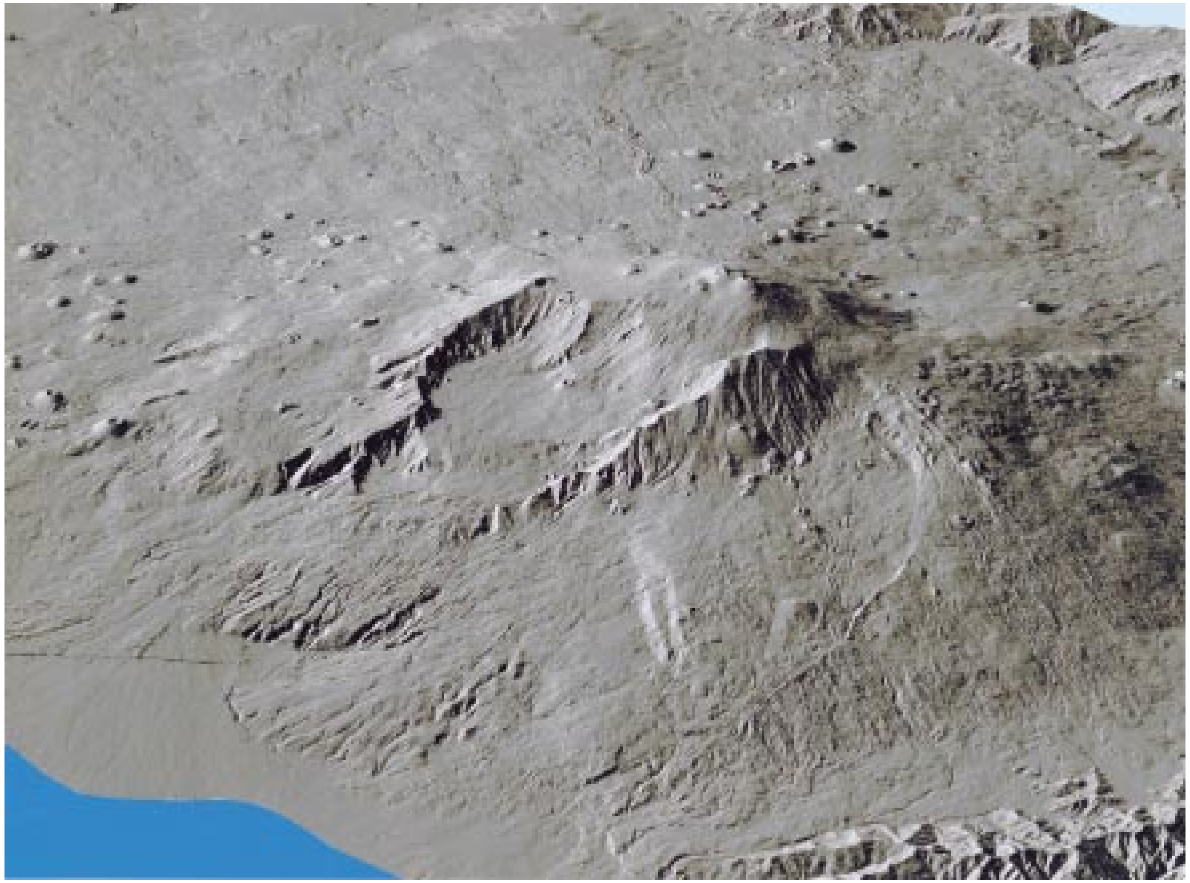

Figure 1. (a) Perspective view of the DEM of Mt. Etna. (b) DEM of the circumvesuvian area. In the foreground there is Vesuvius, in the background the Appennine Mountains toward of Avellino. (c) DEM of the cone; buildings are represented with different colours according to the population density. Blue lines represent the administrative boundary of the towns around Vesuvius. (d) Municipality boundaries around the Vesuvius cone.

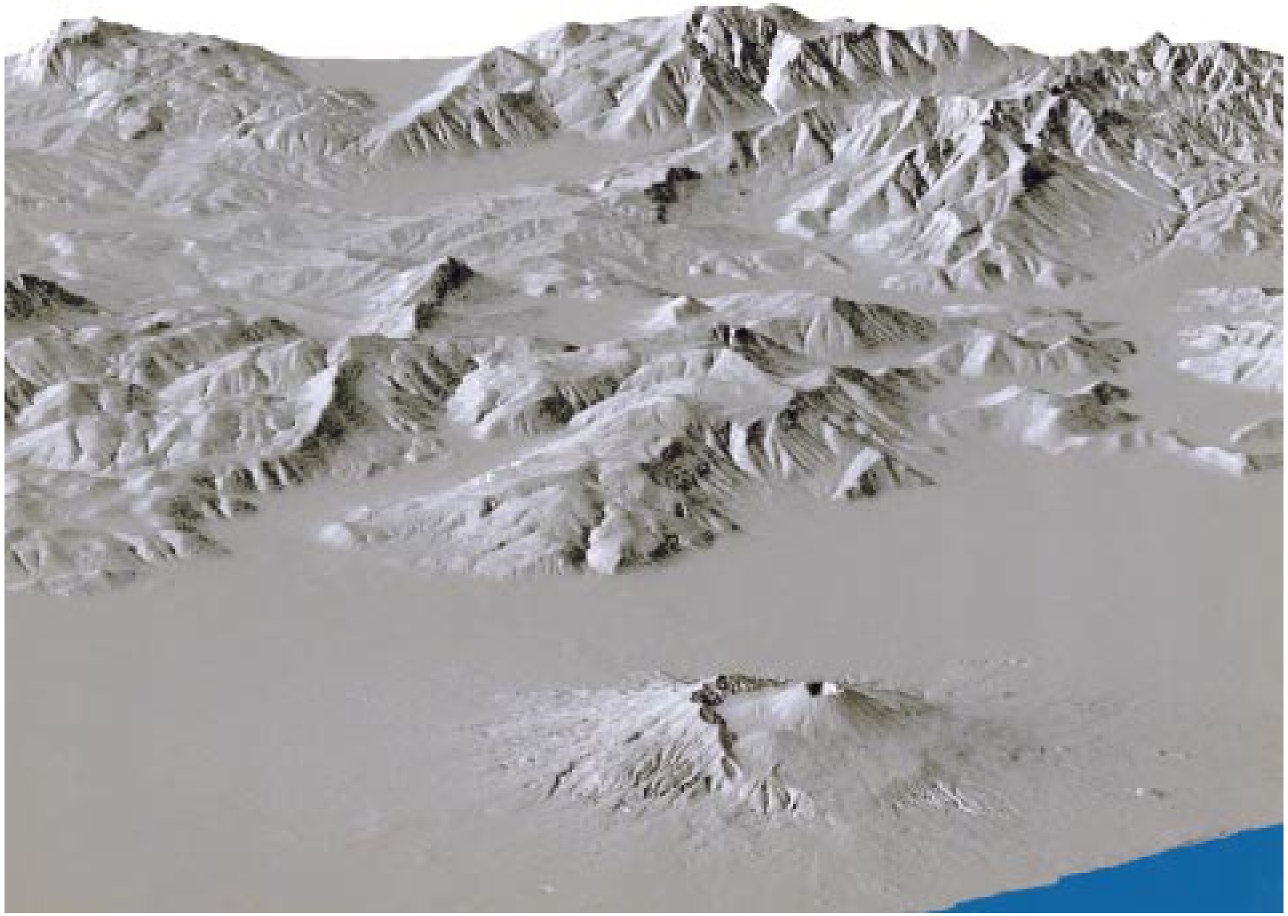

Figure 1. Continued.

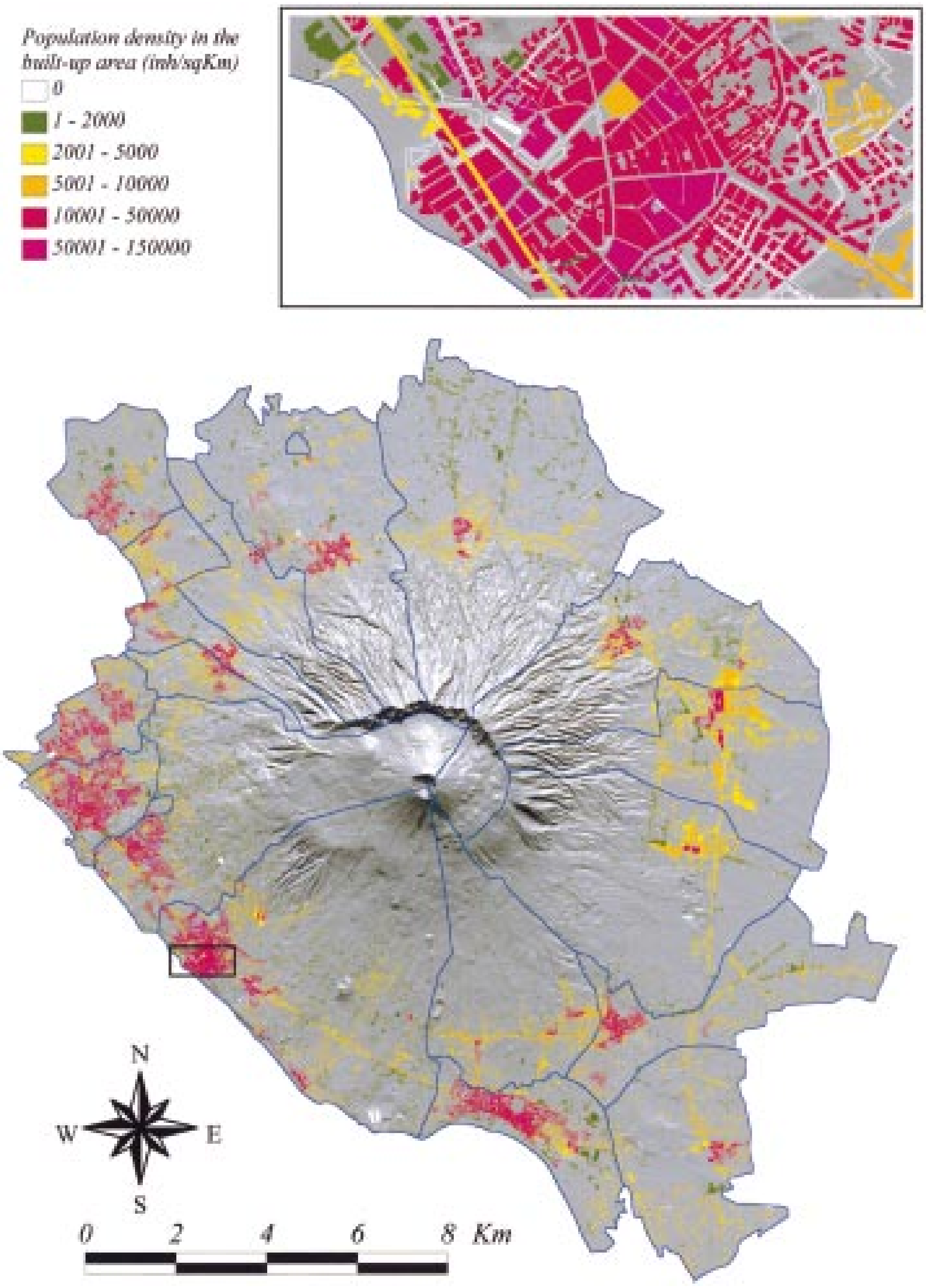

Figure 1. Continued.

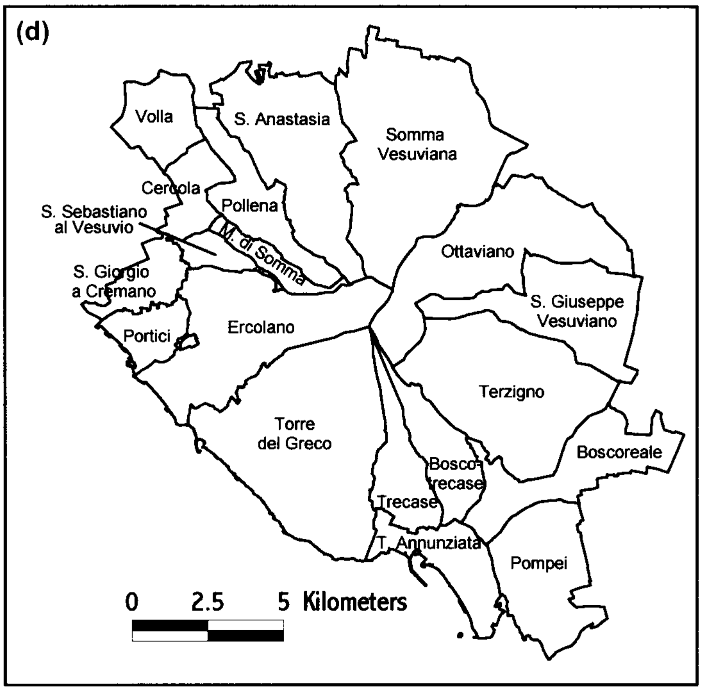

Figure 1. Continued.

From the Mt. Vesuvius DEM additional information was computed: drainage network, slope matrix and watersheds (Figure 2).

2.2. DIGITAL IMAGES FROM SATELLITE OR AIRCRAFT

Main sources are LANDSAT TM (pixel = 30 m), SPOT (pixel = 10 m) and AIMA (pixel resolution = 1 m^2) digital images. These images must be integrated with digital terrain to have coincident maps of the same scene. Segmentation and pattern recognition techniques on remote sensing data can be used to gather measurements of landscape features (soil type and boundaries, vegetation, inhabited areas, etc.). In particular some recent AIMA images (May 1997) have been used to identify the rapid urban increase occurring in recent years (in some cases, illegal buildings).

2.3. VECTOR DATA ON NATURAL AND ARTIFICIAL FEATURES

The information includes the position and types of natural and man-made features. Each of the information items is tagged according to georeferenced lines and identified by an appropriate layer. Furthermore, (at least for the most important items) an alphanumeric chart and one or more digital images show their conditions. The layer allows identification, like that of a transparent page in an anatomy atlas, of

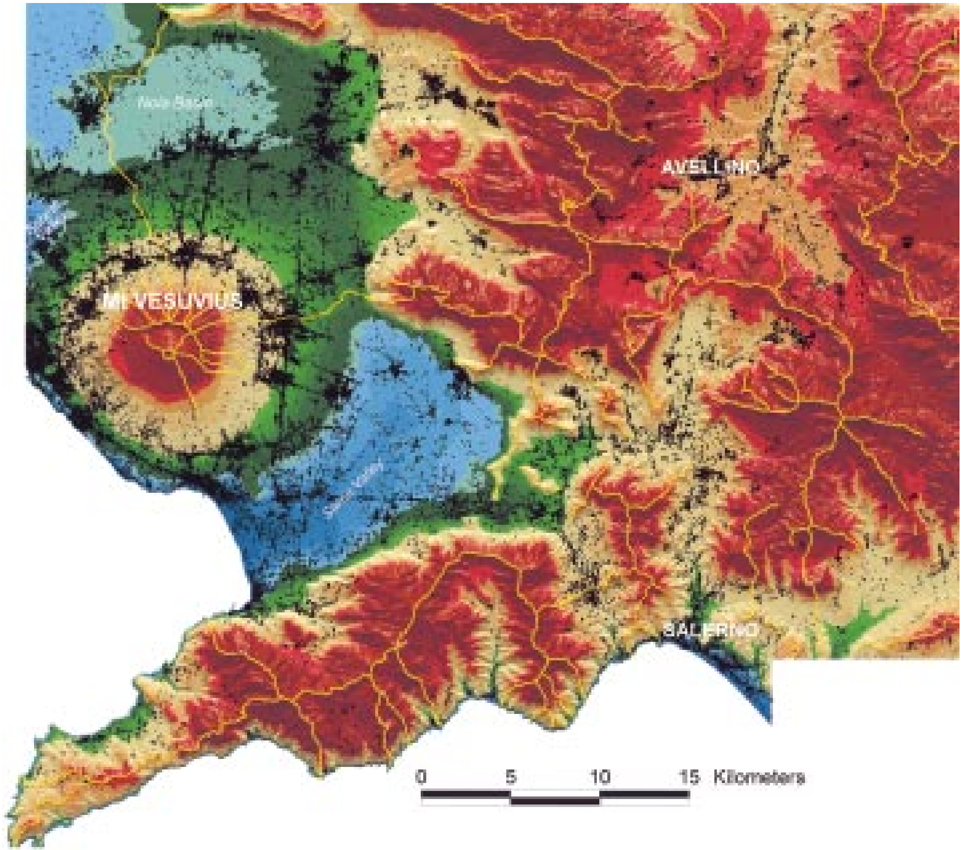

Figure 2. Altimetric map of Vesuvius and surrounding areas. Cyan colours indicates quotes below 30 m.The yellow lines represent watersheds.

items of a similar type. Similarly all the items of the same type or different types can be visualised, allowing subtractions or additions of the various typologies.

The vector layers of the GIS for Mt. Vesuvius in the proximal area are: elevation contours, spot heights, hydrography, buildings, roads (footpath, roads and motor ways), railways, place names, administrative boundaries, principal lifelines (Figures 1(c), 3(a)). Some of these layers include sublayers. For example buildings are further distinguished in: industrial buildings, administrative buildings, green-houses and canopies, archaeological structures (Figure 3(b)), other buildings.

A graph of the roads is developing for the Vesuvian area, connected with information on population to provide help in the drawing up of an evacuation plan.

The main layers of the external area around the volcano, derived from a map at an original scale of 1 : 25,000 and from remote sensing images, are: inhabited areas, contour lines, main roads, railways, supply lines (electric lines, water systems, gas pipelines), place names.

For the Mt. Etna region, layers of the GIS are: roads (motorways, four-lane roads, main roads, other roads, dirt roads and car tracks, bridle paths and footpaths), railway lines, stations and tunnels, hotels, camp sites, mountain huts, historical buildings (castles, museums, archaeological monuments, ruins, etc.), municipal and provincial boundaries, inhabited areas, place names.

For both the regions, other information regarding social/public (i.e., banks, hospitals, etc.) and economic activities (chemical, textile, etc. manufacturing activities, production and distributions of gas, water, etc.) is available. The source is the 1991 census by ISTAT. Data are available for city neighbourhoods. Table I reports the main layers according to data organisation. Each layer is further organised in sublayers and in groups (as an example Table I reports the sublayers of the layer manufacturing activities and the groups of some sublayers). Such information (for example location of the industries dealing with inflammable material) can be used to evaluate induced risk too.

2.4. HAZARD MAPS

Hazard quantification is one of the prime aim of modern volcanology. Today, in the compilation of a hazard map, the most commonly used approach is based on the identification of areas affected by past eruptions. The basic assumption is that events of the same type in the future strike the same areas in the same way and with the same average frequency as in the past. The longer the period of reliable data available and the greater the amount of data, the more reliable is the assessment of the degree of danger. The available hazard maps, either simple sketches or based on a quite detailed basis, represent a sub-division of the land affected in the past with various frequencies by destructive volcanic phenomena.

An alternative/integrative estimate of the hazard can be obtained with the aid of mathematical models that simulate the evolution of volcanic phenomena and

(a)

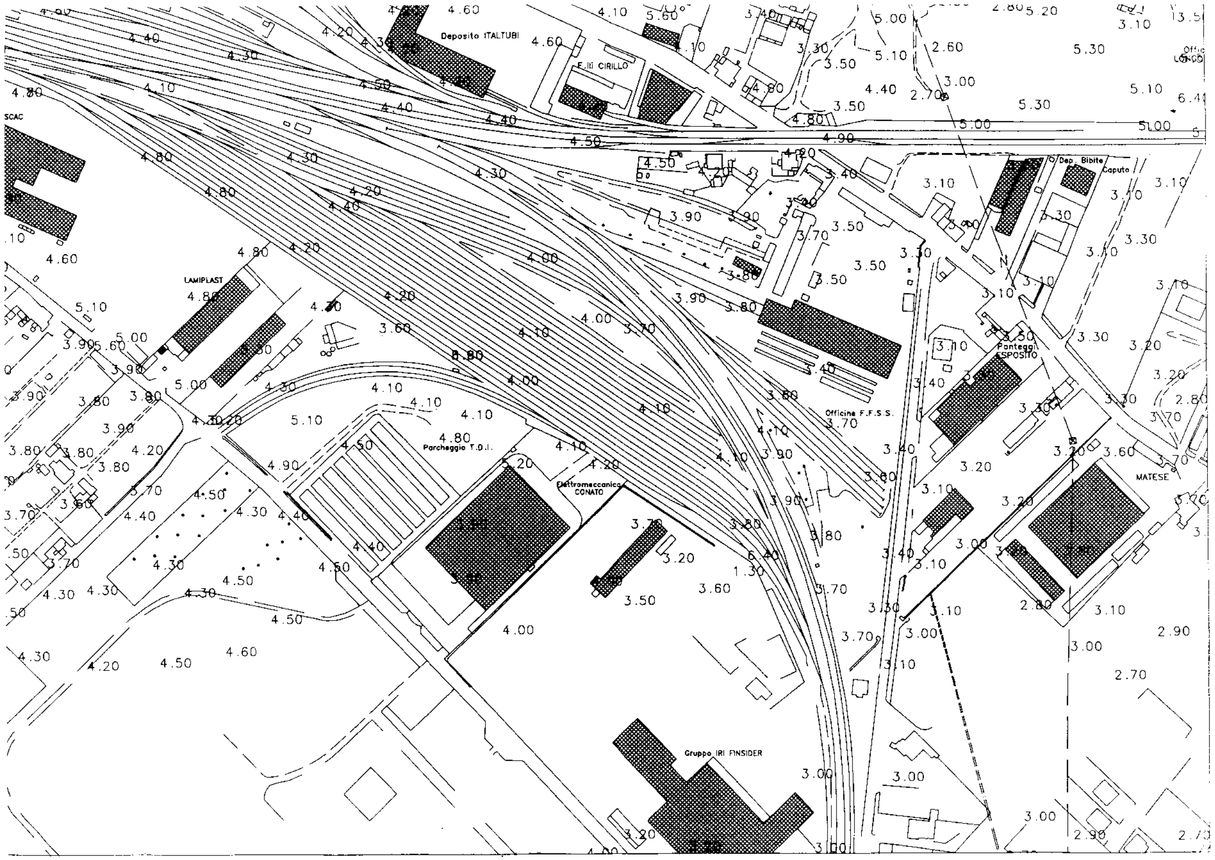

Figure 3. (a) A particular of the GIS around Vesuvius (Torre Annunziata railway station). Example of one vector layer is shown (quotation points, railway tracks, buildings, industrial buildings, streets, etc.); (b) A layer of the GIS refers to the archaeological structures: particular of the ancient city of Pompeii.

Figure 3. Continued.

Table I. (a) The main layers of the social/public and economic activities. (b) Sublayers and groups of the main layer of manufacturing activities. (c) Groups of some sublayers of the main layer of manufacturing activities

Main layers of social/public and economic activities
Agriculture, Hunting And Forestry
Fishing, Fish Farming And Connected
Mineral Mining
Manufacturing Activities
Production And Distribution Of Electricity, Gas And Water
Construction
Wholesale And Retail Trade; Repair Of Vehicles, Motorcycles And Personal/Household Goods
Hotels And Restaurants
Transport, Storage And Communications
Monetary And Financial Intermediation
Estate Agencies, Information Technology, Research, Other Professional And Entrepreneurial Activities
Public Administration And Defence; Compulsory Social Insurance
Education
Health And Other Social Services
Other Public, Social And Personal Services

Table I a)

Sublayers of the Layer Manufacturing Activities
Food, drink and tobacco industries
Textile and clothes
Tanneries, manufacture of leather and similar products:
Wood industry and wood products
Manufacture of paper pulp, paper and paper products, printing and publishing
Production of coke, oil refineries, treatment nuclear combustibles
Production of chemical products, synthetic and artificial fibres
Manufacture of rubber
Manufacture of products
Production of metal and metal products
Production of mechanical machines and equipment, include installation, assembly, repair and maintenance
Manufacture of electrical machines and electrical and optical equipment
Manufacture of vehicles
Other manufacturing

Table I b)

Groups of some sublayers of the Manufacturing Activities
Wood industry and wood products
Manufacture of veneers, plywood, stratified panels fibre/particle panels and other panels
Manufacture of wood fixtures for building industry
Manufacture of wooden crating
Manufacture of other wood products, cork and straw articles and basketwork
Shoe manufacture
Manufacture of paper pulp, paper and paper products, printing and publishing
Manufacture of paper pulp, paper and paper products, printing and publishing
Manufacture of paper and cardboard products
Publishing
Printing and connected services
Reproduction of recorded media
Production of coke, oil refineries, treatment nuclear combustibles
Manufacture of coke products
Manufacture of refined petrol products
Treatment of nuclear combustibles
Production of chemical products, synthetic and artificial fibres:
Production of basic chemical products
Production of pesticides and other chemical products for agriculture
Production of paints, varnishes and enamels
Manufacture of pharmaceutical products and chemical and botanical products for medicinal use
Production of soaps and detergents, cleaning and polishing products, perfumes and toilette products

Table I c)

compute the effects at the ground level, allowing estimation of the area affected by a volcanic event. In this way it is possible to take into account the present state of the volcano and to refer to a precise scenario in order to assess the present hazard. As an example, Figure 4 presents a hazard map at Vesuvius, where the event of 1631 is used as the maximum expected eruption. During the last 2,000 years, the volcano had eruptions ranging between VEI 5 to 0–1, the 1631 VEI was 4 (Rosi *et al*., 1993). Since last eruption of Mount Vesuvius was in 1944, hypothizing a roughly constant deep magma supply, 0.2 km^3 of magma could be today available in a magmatic chamber below the volcano (Santacroce *et al*., 1994; Santacroce *et al*., 1998). If this magma was erupted at once, the volume of the reference eruption should be similar to that of 1631. Three main regions are reported in Figure 4, according to the corresponding main volcanic phenomena expected: (a) the area around Vesuvius potentially exposed to proximal phenomena (including pyroclastic flows, surges and lahars), (b) the area potentially exposed to roof collapse due to ash fallout (thresholds 400, 300 and 200 Kg/m^2) and (c) floods invasion, computed by using the DEM (Armienti *et al*., 1988; Barberi *et al*., 1990; Barberi *et al*., 1992; Macedonio *et al*., 1988; Santacroce *et al*., 1994; Longo *et al*., 1997; Santacroce *et al*., 1998). Area at point (b) has been estimated by a numerical model simulating ash dispersion (Macedonio *et al.*, 1988, Barberi *et al.*, 1990), corresponding to different wind profiles and granulometric distributions (controlling settling velocities). About 3,000 simulations have been performed, corresponding to the measured wind profiles of 10 years. The probability to have an ash load greater than a given % (collapse threshold) is computed as a ratio of such occurrences over the total number of simulations.

A computer simulation approach allows us to deal with on-going phenomena controlled by topography. For Mt. Etna for example, maps for lava invasion can be computed based on a maximum slope – statistical approach (Macedonio *et al*., 1990). It is possible to interactively assign the lava vent and to estimate the hazard map (with average computational times of 1 min on a PC 200 MHz, 64 MB Ram) superimposed on a shadowed georeferenced image of Mt. Etna and other GIS layers (including place names).

2.5. POPULATION DENSITY

In the Vesuvian and Etnean areas information about population are available. The data come from the 1991 Istat Census. Further population classes take account of sex, education, age, etc.

Population density is critical in the Vesuvian area. More than 600,000 people live in the proximal zone (230 km^2, including the cone). One half (about 334,000) of them live in an area of about 15 km^2, with an average density of 22,000 inh/km^2, and peak values of 150,000 inh/km^2 (in the census areas, corresponding to town neighbourhoods). Table II reports information on the population living near Vesuvius, subdivided in administrative municipalities (Figure 1(d)). The maximum

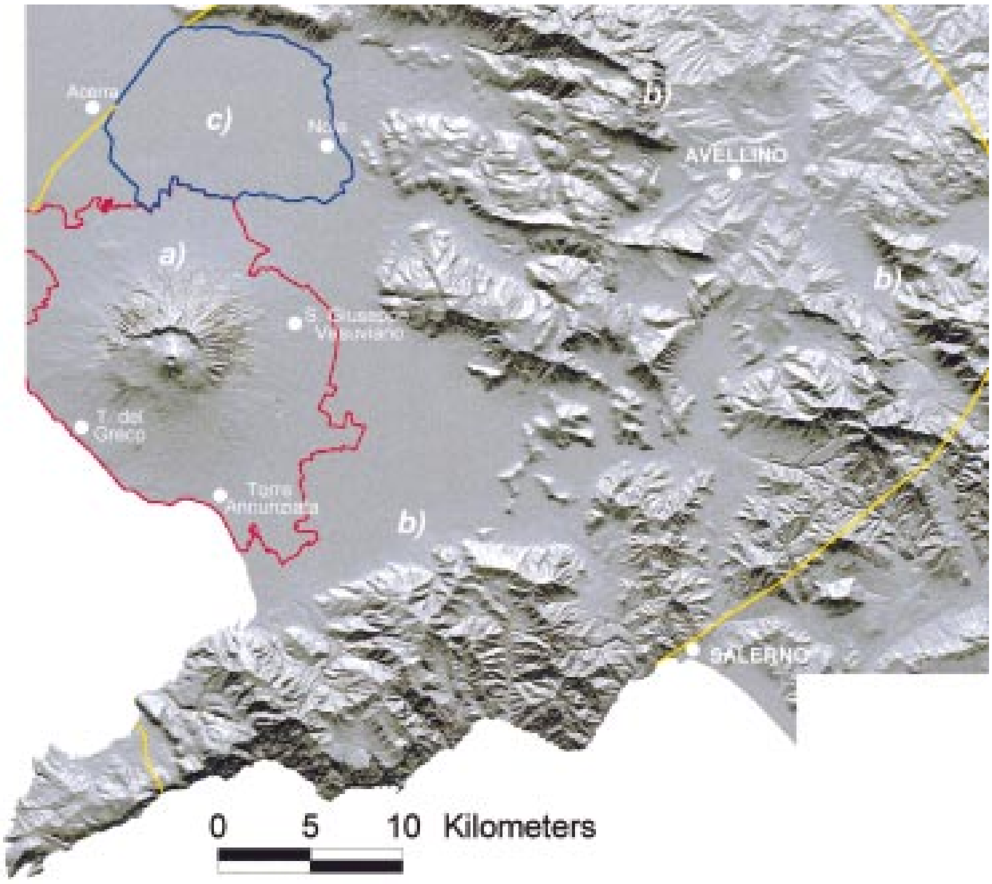

Figure 4. Hazard volcanic map of the Vesuvian area: (a) area exposed to proximal phenomena; the boundaries are those of the 19 municipalities around the cone, (b) area exposed to fallout (and lahars), the boundary defines the area of isoprobability 5% of having tephra blankets heavier than 200 Kg/m^2, (c) area exposed to floods (and fallout) (after Barberi *et al*., 1992; Santacroce *et al.*, 1998).

concentration of population is reached along the coast, South-West of the cone. In the case of an evacuation due to an impeding volcanic crisis, serious problems could arise, since this coastal area is bordered by the Vesuvius cone, the sea and the city of Naples (where 2 million people live).

3. Risk Management by a GIS

GIS strategy can be a powerful instrument to manage all the data above mentioned to civil protection aims. More specifically, GIS may be used:

To compile risk maps, by the output of numerical simulation models evaluating hazard, the distribution of products of past eruptions, soil characteristics, land fea-

Table II. Information on the population living near Vesuvius, subdivided in administrative municipalities (see Figure 1(d)). Columns 5 and 6 report the population in 1981 and 1994. The number of the economical activities and public social activities (and the people involved) is reported in columns 7 and 8. Data are derived from the ISTAT census of 1991

	Area (km^2)	People in 1991	Average density (ab/Km^2)	People in 1981	People in 1994	Economical activities	People involved	Social-public centres	People involved
Administrative municipalities east of Vesuvius									
Boscoreale	11	27,310	2,419	21,911	27,831	808	1,839	44	613
Cercola	4	16,901	4,001	19,797	18,009	455	2,014	38	395
Ottaviano	20	21,973	1,103	19,787	22,516	864	2,594	46	948
Pollena Trocchia	8	12,216	1,531	8,661	12,984	309	998	21	303
S. Anastasia	19	27,396	1,475	22,495	28,835	963	2,468	55	1,134
S. Giuseppe Vesuviano	14	26,336	1,868	23,530	26,757	1,703	4,550	61	835
Somma Vesuviana	31	29,079	952	22,897	31,165	906	2,535	49	840
Terzigno	23	13,653	584	10,835	14,665	674	1,547	29	390
Administrative municipalities west of Vesuvius									
Boscotrecase	7	11,295	1,507	12,032	11,049	400	974	26	343
Escolano	20	61,233	3,082	57,495	60,130	1,713	4,641	113	1,896
Massa Di Somma	3	5,492	1,835	n. a.	5,980	120	342	12	117
Pompei	12	25,177	2,036	22,896	26,118	1,676	4,868	109	1,623
Portici	4	68,980	15,390	79,259	65,319	2,275	5,461	114	2,955
S. Giorgio a Cremano	4	62,258	15,161	61,271	61,296	2,447	5,953	93	2,075
S. Sebastiano al Vesuvio	3	9,486	3,600	8,816	10,016	436	1,421	26	404
Torre Annunziata	7	52,875	7,132	57,097	50,744	1,610	6,712	103	3,393
Torre del Greco	30	101,361	3,324	102,980	99,556	3,008	8,341	162	4,452
Trecase	6	9,595	1,552	8,760	10,012	240	579	30	244

Table III. Vulnerability (% roof collapses) depending on ash load (Angeletti *et al*., 1998).

Estimated roof collapses load (kg/m^2)	%
100	2
200	7
300	19
400	42
500	67
600	89

Table IV. Damage (roof collapse) in a 1631-like Vesuvius eruption. The data refer to the area between L and L + 100 (kg/m^2)

Ash load (L) kg.m^2	Area (Km^2)	Total No. of flats	Total No. of rooms	Total No. of collapsed flats	Total No. of people living in the area
100	104	15,207	61,514	304	43,501
200	147	24,655	97,511	1,726	69,866
300	57	7.362	29,342	1,399	22,514
400	42	8,767	35,793	3,682	28,592
500	6	1,571	6,846	1,058	5,143
600	8	57		51	199
Total	364	57,619	231,233	8,220	169,815

tures, information about value and vulnerability. Risk maps of this kind can be an help for land use planning. An example was realised for Vesuvius. Risk for tephra fallout was computed as the product of hazard (previously discussed), vulnerability and value (=1 where buildings are present, 0 otherwise). The resulting map (Barberi *et al.*, 1990) can be used for land planning.

As a further application, the estimate of the roof collapse damage caused today by an event similar to that of 1631 has been evaluated. Vulnerability related to different ash loads (Cherubini, private communication) is shown in Table III. The 1631 deposits (Figure 5) come from Rosi *et al*. (1993). The domain considered is that inside the threshold of 100 kg/m^2. The number of buildings and of inhabitants are available from the GIS. The number of probable building collapses come form the number of effective buildings time the vulnerability (depending on the load). Table IV reports the number of collapses as function of ash load (Angeletti *et al.*, 1998).

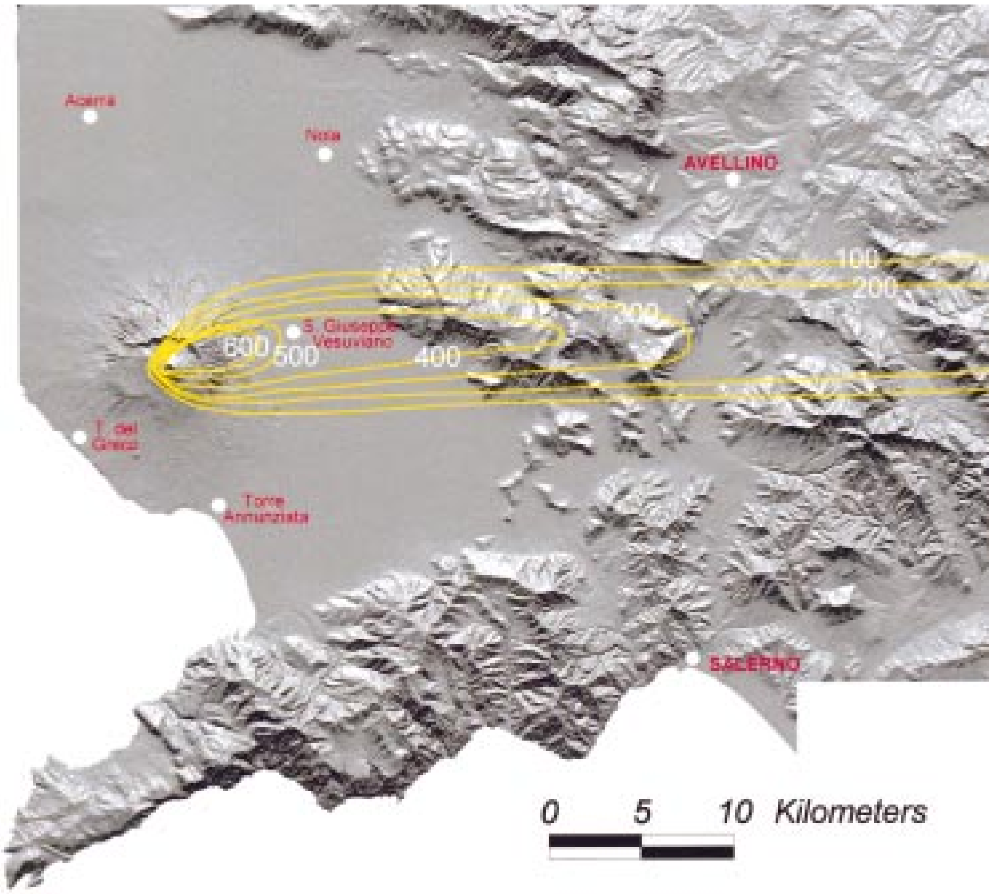

Figure 5. The ash fallout (kg/m^2) of the 1631 eruption (after Rosi *et al*., 1993) superimposed to the GIS layers.

To minimise risk. Combined information on land use and on hazard can be used to choose a suitable strategy to risk reduction. For example, in the case of Mt. Etna, it is possible to evaluate the area potentially affected by lava flow and so to identify the man-made features (buildings, roads, cultivation, etc.) potentially involved. This allows to choose the suitable strategy (i.e., location of an artificial barrier or of a channel) to minimise losses. Figure 6 shows the case of 1991–1992 eruption. The model adopted shows that the city of Zafferana is potentially at risk, but there is a strong morphological control by a narrow passage West of Mt. Calanna. A barrier effectively built in that place deviated the flow (Barberi *et al*., 1992).

To draw evacuation plans, by population information, road graph, hazard maps, etc.

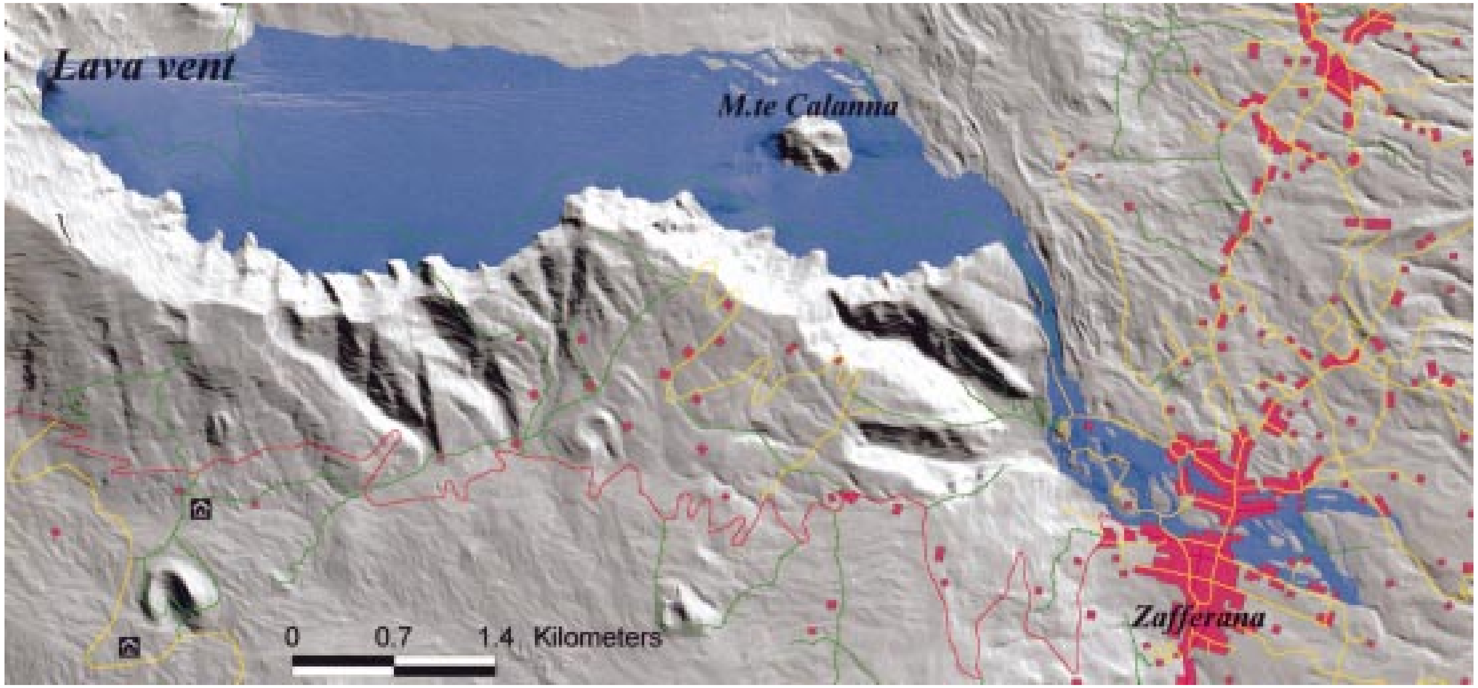

Figure 6. 1991 Mt. Etna eruption. Simulations suggested that a barrier built in a narrow passage West of Mt. Calanna prevented the city of Zafferana from lava invasion. The figure shows the area (blue) potentially interested by lava without the barrier. The layers of the GIS are: streets (yellow), pathways (green), buildings (red).

To deal with an impending or an on-going eruption, to the evaluation of alternative spatial strategies according to precise events (for example the opening of a new lava vent).

To have a record of buildings, economic resources, people, etc., in the case of a complete destruction. An example comes from the recent mud flows at Sarno-Quindici (5 May 1998), remobilizing ancient ash fallout of Vesuvius. These secondary lahars have completely buried tens of houses and caused the death of over 150 people. The GIS, with its metric information, allows to know the exact spatial location of houses and provide information of the points where possible buried survivors must be looked for.

There is a great difference in the behaviour of Mt. Etna and similar volcanoes (characterised by low-viscosity magmas and consequently by an effusive activity involving phenomenon time scales of many days) and explosive volcanoes as Vesuvius (the time scale is few minutes for pyroclastic flows and one day for fallout). At both volcanoes, GIS strategy appears more or less useful in land planning or in the preventive assessment of an evacuation strategy or to deal with an on-going crisis, primarily depending on the time scales of the volcanic phenomena and of the actions to be taken.

Acknowledgements

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