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A GIS-based approach for estimating volcaniclastic flow susceptibility: a case study from Sorrentina Peninsula (Campania Region)

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ABSTRACT

With the aim to improve volcaniclastic flows hazard zonation and risk mitigation in volcanic areas, this work presents a GIS-based study on the Sorrentina Peninsula, located southwest of the main Neapolitan volcanoes (Ischia, Procida, Campi Flegrei, and Somma-Vesuvius; Campanian Plain, Southern Italy). This area has been heavily affected by historical events with more than 200 volcaniclastic flows recorded in the last 500 years. The study here proposed combines different information, including morphometry, geology, volcanology and land use for building a susceptibility index (named VFSI) able to rank the drainage basins potentially prone to generate volcaniclastic flows. The resulting susceptibility map classifies 488 drainage basins into three different classes (low, moderate and high) over an area of about 280 km^2. The proposed method allows the rapid ranking of the different drainage basins, and is propaedeutic to detailed investigation on single basins for individuating areas more prone to colluvial cover failure and associated volumes of available material for volcaniclastic flow generation.

Key words: *Volcaniclastic flows, GIS, susceptibility index (VFSI), Sorrentina Peninsula, volcanic hazard, Neapolitan volcanoes.*

INTRODUCTION

Volcaniclastic flows are among the most recurrent and dangerous natural hazards in volcanic areas affected by pyroclastic deposition. They can be initiated by various mechanisms, among which the most common are intense and/or prolonged rainfall (Arguden & Rodolfo, 1990; Rodolfo & Arguden, 1991; Pareschi *et alii*, 2000; Scott *et alii*, 2001), breakouts of crater lakes (Mastin & Witter, 2000; Giordano *et alii*, 2002; Procter *et alii*, 2010), melting of snow or glacial ice during an eruption (e.g. Lowe *et alii*, 1986; Pierson, 1995), or seismic triggering of landslides that evolve to debris flows (e.g., White *et alii*, 1997; Sheridan *et alii*, 1999; Scott *et alii*, 2001). They can originate not only during or shortly after an eruption (syn-eruptive; Sulpizio *et alii*, 2006) but also during a period of volcanic quiescence (inter-eruptive), when heavy and/or persistent rainfall remobilises loose pyroclastic deposits (e.g. Siebe *et alii*, 1999; Pareschi *et alii*, 2002; Zanchetta *et alii*, 2004a, 2004b).

Several works have analysed the hazard related to volcaniclastic mass flows through the reconstruction of historic and prehistoric events (e.g., Scott, 1989; Scott *et alii,* 1995; Vallance & Scott, 1997; Bisson *et alii*, 2007a), using empirical relationships (Iverson *et alii*, 1998; Pierson, 1998; Scott *et alii*, 2001; Toyos *et alii*, 2007) or physically based models (e.g. Macedonio & Pareschi, 1992; Costa, 1997; Pitman *et alii*, 2003). The hazard related to volcaniclastic mass flows extends well beyond the volcanic slopes, including other mountainous areas subjected to pyroclastic fall deposition (e.g., Siebe *et alii*, 1999; Pareschi *et alii*, 2000, 2002; Zanchetta *et alii*, 2004a, 2004b). Volcaniclastic mass flows in such areas might produce extensive damage and casualties in distal areas considered safe or little affected by other volcanic hazards (e.g. pyroclastic fall, pyroclastic density currents, volcanic landslides).

In the mountainous area downwind of Somma-Vesuvius and Campi Flegrei volcanoes (Campania region, southern Italy, fig. 1), the risk related to volcaniclastic mass flows is very high and can be separated in long and short term (Zanchetta *et alii*, 2004a; Sulpizio *et alii*, 2006). The Sarno-Quindici event of 5-6 May 1998 is a dramatic example of the long-term hazard in the area. This event occurred 54 years after the last eruption of Somma-Vesuvius (AD 1944; Santacroce *et alii*, 2008) and ~400 years after the last large explosive eruption of Somma-Vesuvius that deposited a significant thickness of pyroclastic material in this area (AD 1631 eruption; Rosi *et alii*, 1993). The failure of large portions of the colluvial cover that mantles the Apennine Mountains generated a number of volcaniclastic debris flows that inundated several settlements near the bases of hill slopes, killing more than 150 people (e.g. Pareschi *et alii*, 2000; Zanchetta *et alii*, 2004a).

Events like this are common in the sub-Apennine basins of the Campanian plain affected by pyroclastic deposition in the period (AD 1631-1944). Major volcaniclastic flows occurred in 1954 at Villaggio di Vettica (30 deaths), in 1924 at Amalfi (30 deaths), in 1910 at Regina Major (a suburb of Maiori village) and Cetara (60 and 110 deaths, respectively), in 1841 at Mulino delle Capre (120 deaths), in 1823 at Salerno-Positano-Siano-Tramonti (120 deaths), in 1764 at Gragnano (43 deaths) and in 1640 at Sarno (40 deaths; Migale & Milone, 1998). In addition, 40 debris flow episodes occurred in the Sarno area in the two centuries prior to 1998 (Migale

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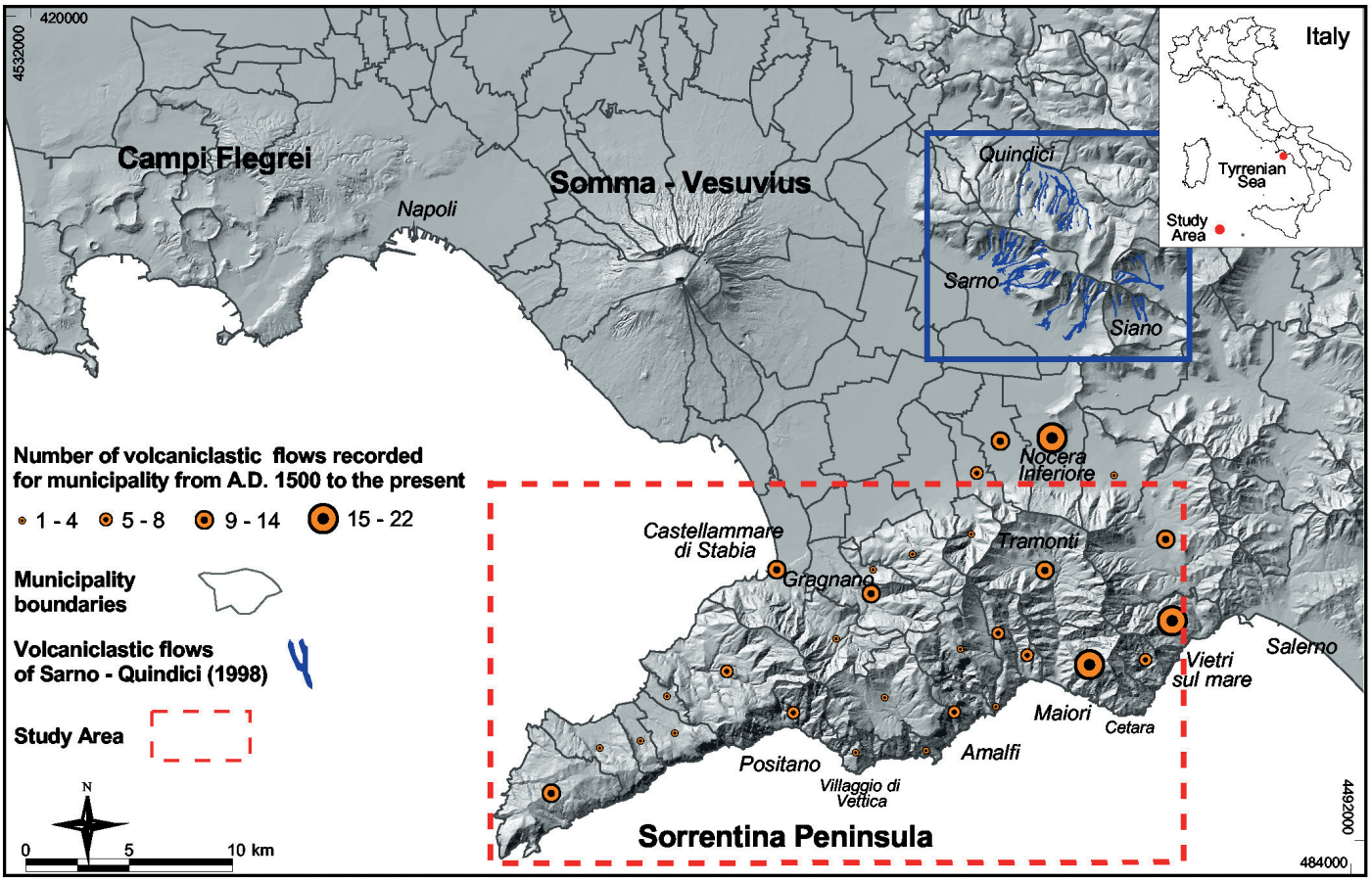

Fig. 1 - Location of the study area. The metric coordinates are in the WGS 84 - UTM - Zone 33 Reference Cartographic System.

& MILONE 1998). With the aim to mitigate the volcaniclastic flow-hazard in the Sorrentina Peninsula, a GIS-based methodology is here proposed for a fast and preliminary selection of the areas more prone to be affected by volcaniclastic flows. The proposed approach allows the zonation of large areas combining morphometric analysis of drainage basins, lithology, faults and fracture system, probability of water table formation, and cumulative thickness of pyroclastic deposits. This approach is a useful tool for discriminating among different drainage basins and it is preparatory for detailed susceptibility analysis. The main output is a susceptibility map that ranks the studied drainage basins with respect to volcaniclastic flow generation proneness.

STUDY AREA

The Sorrentina Peninsula is a structural high transversal to the Apennine chain and is located in the western portions of the southern Campania Plain. The investigated area covers about 280 km^2 involving 30 municipalities (fig. 1). From a geological point of view, the bedrock mainly consists of Mesozoic carbonates forming a monocline generally dipping towards the north (CALCATERRA & SANTO, 2004). The overall structural framework of the Peninsula is characterized by major normal and reverse faults, mainly NW-SE (Apennine trend) and NE-SW (anti-Apennine trend) trending, but sometimes showing a horizontal component of displacement. Pyroclastic deposits from the explosive activity of the Somma-Vesuvius and Campi Flegrei volcanoes alternating with volcaniclastic colluvium blanket the Mesozoic carbonates with variable thickness.

DATASETS AND METHODS

HISTORICAL DATASET

The available data on volcaniclastic-flow events of the Campania region (e.g. MIGALE & MILONE, 1998; DEL PRETE *et alii*, 1998; CASCINI & FERLISI, 2003; CALCATERRA *et alii*, 2003; CALCATERRA & SANTO, 2004, BISSON *et alii*, 2007a) were here collected, checked, and reorganised to create a specific database for the Sorrentina Peninsula. Considering the possible incompleteness of historical data and the overweight probably given to large magnitude events (because they usually produce great damage and loss of life), data sets from past events need to be threaded carefully (e.g. CARRARA *et alii*, 2003). In addition, a reported historic event does not necessarily means a single volcaniclastic flow occurrence, because an intense rainfall event can cause multiple volcaniclastic flows over a large area or a number of slurries at different times in a single drainage basin (e.g. the May 1998 events; ZANCHETTA *et alii*, 2004a). Taking into account all these considerations, an event is here defined as a single or a multiple volcaniclastic flow reported by historical accounts in a certain municipality in a short (days to weeks) time interval.

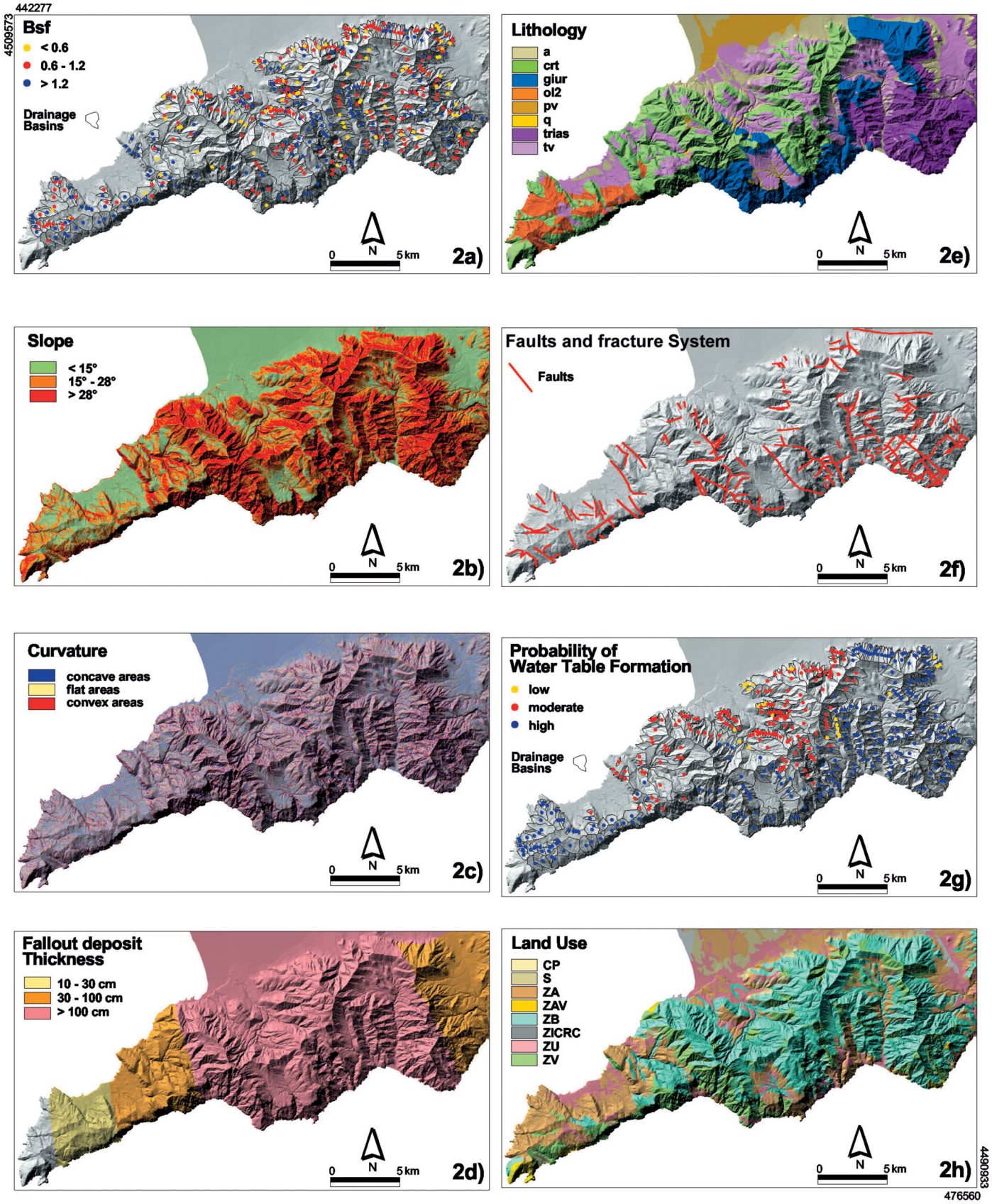

Fig. 2 - The thematic layers used as dataset in this study. For the codes see the text.

TABLE 1

VFSI classification applied to drainage basins affected by the May 1998 Sarno-Quindici event.

id	municipality	slope	bsf	curvature	fall out deposit thickness (cm)	lithology	land use	faults	probability of water table formation	VFSI
1	QUINDICI	26,69	1,93	-0,0001	791,25	crt	ZB	0	moderate	37
2	SARNO	31,00	1,36	0,0000	907,92	crt	ZV - ZB	2	moderate	38
3	SARNO	34,83	1,62	0,0003	894,73	crt	ZV - CP	1	moderate	36
4	SARNO	33,67	1,01	-0,0003	883,73	crt	ZV - ZB	1	moderate	36
5	SARNO	32,15	1,53	0,0003	874,43	crt	ZV - ZB	1	moderate	36
6	SARNO-QUINDICI	32,23	1,38	0,0001	820,94	crt	ZB - ZV	4	high	42
7	SARNO	31,90	0,71	0,0000	781,79	crt	ZV - ZAV	2	moderate	36
9	SARNO	33,32	1,14	0,0001	655,59	crt	ZB - ZV	4	high	40
10	SARNO	32,69	0,84	0,0001	617,06	crt	ZB - ZV	1	moderate	36
11	SARNO	33,02	1,42	0,0002	575,96	crt	ZB - ZV	0	moderate	38
12	SARNO	31,32	0,76	-0,0002	580,94	crt	ZB - ZV	0	moderate	38
13	SIANO	31,94	1,21	0,0001	551,58	crt	ZB - ZV	0	moderate	38
14	SIANO	34,15	1,51	0,0000	548,48	crt	ZB - ZV	0	moderate	39
15	BRACIGLIANO	32,29	0,80	-0,0002	583,91	crt	ZB	0	moderate	38
16	BRACIGLIANO	32,16	0,94	-0,0002	607,38	crt	ZB	0	moderate	38
17	BRACIGLIANO	34,46	1,17	0,0002	616,33	crt	ZB	0	moderate	36
18	BRACIGLIANO	32,51	0,89	-0,0002	646,57	crt	ZV - ZB	0	moderate	36
19	BRACIGLIANO	34,08	1,41	0,0000	653,13	crt	ZV - ZB	1	moderate	37
20	QUINDICI	27,37	1,73	0,0005	877,38	crt	ZB	0	moderate	35
21	QUINDICI	29,56	0,78	-0,0003	874,04	crt	ZB - CP	0	moderate	38
22	QUINDICI	30,33	1,15	-0,0001	866,59	crt	ZB - ZAV	0	moderate	38
23	QUINDICI	30,47	0,58	-0,0002	859,66	crt	ZB - ZAV	0	moderate	36
24	QUINDICI	31,46	1,07	-0,0003	842,94	crt	ZB - ZAV	0	moderate	38
25	QUINDICI	31,66	1,24	0,0001	818,25	crt	ZB - CP	1	moderate	38
26	SARNO	32,69	0,72	-0,0001	746,02	crt	ZV	1	moderate	36
27	BRACIGLIANO	29,86	1,36	-0,0003	647,36	crt	ZV - ZB	1	moderate	38
38	QUINDICI	24,32	1,91	0,0003	870,79	crt	ZB	2	moderate	36
39	SARNO	33,79	1,08	0,0006	926,15	crt	ZV - ZB	3	high	37
48	LAURO - QUINDICI	18,37	5,99	0,0000	895,33	crt - tv	ZB - CP	2	moderate	38
317	QUINDICI	19,35	3,44	-0,0001	877,25	tv - crt	ZB - CP	1	moderate	38
318	SARNO	30,55	1,06	0,0000	718,97	crt	ZB - ZV	4	high	41
319	SARNO	30,99	0,52	0,0000	729,86	crt	ZV	2	moderate	34
787	SIANO	31,99	0,70	-0,0006	494,36	crt - a	ZV	0	moderate	36
792	SIANO	32,04	0,52	0,0001	490,72	crt - a	ZV	0	moderate	32
916	SIANO	28,85	1,10	0,0003	492,11	crt	ZV	0	moderate	34

The database of the Sorrentina Peninsula contains more than 200 volcaniclastic flow events recorded from AD 1540 to AD 1999 and organised within a georeferenced point-vector layer. The number of events in each municipality and the dates of relative occurrences were attributed to the barycentre (centroid) of the polygon representing the boundary of the affected municipality. The number of events recorded in the affected municipalities is evidenced by the size of the dots in fig. 1. Analysing the spatial distribution of historical events, the municipalities more affected by volcaniclastic flows are Vietri sul Mare (22 events), Maiori and Nocera Inferiore (20 events). The localities mentioned for the most disastrous occurrences are Pozzano village and Monte Pendolo (CALCATERRA & SANTO, 2004). The first is located in Castellammare di Stabia municipality and was affected by a landslide on January 10th, 1997, which caused 4 deaths, 22 injuries and roads closure for about 2 months. Monte Pendolo is located within the Gragnano municipality, and was affected by two events in AD 1764 and AD 1841 that caused 41 and 100 deaths, respectively (CALCATERRA & SANTO, 2004).

METHODS

In order to identify the areas more prone to volcaniclastic flow generation, we developed a GIS-based approach combining various information about the drainage basins identified in the study area. Eight thematic layers summarise the information relevant for the method. They are grouped in four different categories: morphometry (slope, basin shape factor, slope curva-ture), volcanology (thickness of cumulative pyroclastic deposits), geology (lithology, faults and fracture system, probability of water table formation), and land use. The thematic layers were organised within a GIS as raster and vector databases geocoded to WGS84 UTM Zone 33 reference coordinate system (fig. 2).

The relative weights of each of the 8 parameters have been evaluated and combined using an equation to obtain the Volcaniclastic Flow Susceptibility Index (VFSI). This index allows to rank the drainage basins for volcaniclastic flow generation proneness. The 8 parameters used for the zonation have been selected, weighted and indexed adopting literature data (ABBATTISTA *et alii*, 2005; LEONI *et alii*, 2009; in press; BISSON *et alii*, 2010) and field survey. The drainage basins disrupted in the Sarno-Quindici event on

TABLE 2

An extract from the drainage basins database. For the meanings of lithology and land use abbreviations see the text.

code	area (mq)	perimeter (m)	municipality	bsf	slope	curvature	fall out deposit thickness (cm)	lithology	faults	probability of water table formation	land use
24	31485	877	TRAMONTI	1,72	29,01	-0,005	122	trias	0	high	ZB
25	39224	959	TRAMONTI	1,13	34,98	0,038	120	trias	0	high	ZB
26	265658	2509	TRAMONTI	0,83	23,89	0,030	134	trias - tv	0	high	ZB - ZA
27	32872	860	TRAMONTI	1,06	36,88	-0,014	117	trias	1	high	ZB
28	635266	3934	CAVA DE' TIRRENI	0,38	25,03	-0,003	81	trias - a - pv - giur	0	high	ZB - ZA
29	108045	1374	RAVELLO	1,75	30,17	0,023	187	tv - a	0	low	ZB
30	705494	3393	RAVELLO	1,20	33,57	0,012	179	giur - crt	4	high	ZB - ZV
31	382648	3367	CAVA DE' TIRRENI	0,80	35,91	-0,008	94	giur - trias - pv - a	0	high	ZB - ZV
32	31473	1179	RAVELLO	0,41	30,38	-0,021	180	giur	1	high	ZB - ZV
33	278750	2367	CAVA DE' TIRRENI	0,78	32,12	0,018	97	trias	1	high	ZB - ZV
34	92745	1304	RAVELLO	0,43	35,07	0,038	181	giur	1	high	ZB - ZV
35	166581	2566	SCALA	0,96	27,71	-0,001	197	crt - tv - a	0	moderate	ZB
36	118050	1618	RAVELLO	1,25	28,58	-0,061	187	tv - a	0	low	ZB
37	62676	1089	RAVELLO	1,66	26,58	0,080	188	tv - a	0	low	ZB
38	1157028	4597	TRAMONTI	1,01	33,77	0,012	165	giur - trias	1	high	ZB - ZV
39	112920	1512	VIETRI SUL MARE	1,31	29,69	-0,003	84	trias	0	high	ZB
40	148663	1837	VIETRI SUL MARE	0,61	27,74	0,037	79	trias	0	high	ZB
41	377116	3186	SCALA	1,02	28,74	0,005	198	crt - tv	0	moderate	ZB
42	135555	1921	TRAMONTI	0,65	35,84	-0,027	134	trias - tv	0	high	ZA - ZB
43	429778	2967	RAVELLO	1,16	34,32	0,024	185	giur - trias	1	high	ZV - ZB - ZU
44	570408	3602	TRAMONTI	0,46	33,61	0,005	164	trias - giur - tv	2	high	ZB - ZA
45	39563	943	RAVELLO	1,40	28,81	0,049	191	tv - a	0	low	ZB
46	300589	2292	TRAMONTI	1,66	39,38	0,045	118	trias	0	high	ZB
47	88729	1620	VIETRI SUL MARE	1,26	25,95	0,018	73	trias	1	high	ZB
48	45622	1038	RAVELLO	0,49	31,14	-0,062	181	trias	0	high	ZB
49	34321	836	RAVELLO	1,54	28,47	0,045	191	tv - a	0	low	ZB
50	141789	1894	RAVELLO	1,86	32,53	0,000	187	giur - tv - trias	1	high	ZV - ZB - ZU

May 1998 (fig. 1 - see the blue inset) have been used as test case. The VFSI applied to 35 of these drainage basins indicates that more than 90% of them classify as high susceptibility areas (tab. 1), confirming the reliability of the VFSI and the weights adopted. Calculations have been performed using the ESRI platform ArcGIS 9.3 software.

Drainage Basins Layer

The drainage basins represent the source areas for volcaniclastic flow generation and are here considered the reference thematic layer for our investigation. This layer consists of 488 polygon features (fig. 2a), whose boundaries are defined as the limit of the watershed as automatically drawn from the digital elevation model (DEM), using a spatial resolution of 10 m. Each drainage basin delimited a second- or third- order hydrographic network obtained using a dedicated tool available in the ArcGis software. The DEM was obtained from a TIN (Triangular Irregular Network) derived by interpolating 3D vector data (contour lines and height spot) from different cartographic sources: digitalization of IGM (Military Geographical Institute) raster maps at 1:25,000 scale (updated to 1980; BISSON *et alii*, 2007b) and vector cartography at 1:2,000 scale (1987 source). The TIN was built using the DEST algorithm (Determination of Earth Surface Structures) that represents a variation of the Delaunay method (FAVALLI & PARESCHI, 2004). This algorithm solves the problem of false flat morphological features introduced by triangles obtained interpolating the vertices belonging to a same contour line. It does so by adding break-lines to these artificial flat areas, thereby creating a more detailed three-dimensional skeleton of the TIN. This greatly improves the computation of morphological features such as ridges, gullies, channel slopes and the drainage network, allowing a more accurate representation of the actual terrain. Subsequently, the TIN was transformed in an elevation matrix and memorized in GRID ESRI format.

The 488 drainage basins have been stored in a vector polygon layer (shapefile format) and the associated table was compiled inserting alphanumerical information about each basin: Code, Area, Perimeter, Municipality and a series of data derived from the analysis of parameters used in the VFSI equation and described in the following subparagraphs. An extract from this database is reported in the tab. 2.

Morphometric Parameters

– The Basin Shape Factor (BSF - fig. 2a)

The BSF is a static morphometric parameter that describes the geometry of the drainage basin (PARESCHI *et alii,* 2000) using the As/Ai ratio, where As and Ai represent the upper and lower areas of the basin with respect to the average height line, respectively. Drainage basins with a BSF of more than 1 (As>Ai) have a greater capacity to collect water in their upper portions and convey it toward the central channel. This can enhance erosion at the bottom of the channel, favouring the destabilization of the volcaniclastic cover. The upper portions of the basins with a

high BSF have also wider steep-slope areas, due to the common morphological profile of the hillslopes in the study area. Because the slope is one of the most important parameters for triggering soil slip (MEJÍA-NAVARRO *et alii*, 1994; BOVIS & JAKOB, 1999; PARESCHI *et alii,* 2002) the basins with high BSF are statistically more prone to generate volcaniclastic flows. The values of BSF are reported in the database of the drainage basins layer (see tab. 2). The map of BSF is shown in fig. 2a through points (geometric barycentre of each drainage basin) coloured according the 3 classes (PARESCHI *et alii*, 2000, 2002) that will be described in more detail in the VFSI section.

– Slope (SL - fig. 2b)

This parameter is represented by a raster layer (fig. 2b) having spatial resolution of 10 meters and stored in GRID ESRI format. Each cell memorises the value of slope expressed in angle and obtained processing the elevation matrix above described, according to the formula of BURROUGH & MCDONELL (1998). Slope is one of the most important parameters for the initiation of any type of landslide because it directly controls the balance between resistant and gravitational forces. In case of heavy or prolonged rainfalls, slope thresholds for the generation of volcaniclastic flows in the Campania area are considered 25°-28° (e.g., DE RISO *et alii,* 1999; CALCATERRA *et alii,* 1999, 2000; PARESCHI *et alii,* 2000, 2002; ZANCHETTA *et alii,* 2004a). From this matrix, the average value of slope for each basin was calculated and inserted in the relative database (see tab. 2).

– Curvature (CURV - fig. 2c)

Also the curvature parameter is represented by a raster layer (see fig. 2c) having spatial resolution of 10 meters and stored in GRID ESRI format. The parameter distinguishes between cells having convex, flat and concave surfaces, respectively. Each cell memorizes a dimensionless numeric value (positive, null, negative) that indicates changes in slope. This layer has been obtained applying to the elevation matrix the second derivative, obtained by combining curvature data along contour lines with those along gradient lines, according to the method of ZEVERBERGEN & THORNE (1987). Also in this case, the average value of curvature of each basin was calculated by this matrix and inserted in the alphanumerical database of drainage basin layers (see tab. 2). Areas with a concave topography play an important role because they preferentially collect water and colluvium: sliding is triggered when the forces promoting mass movement (e.g., gravity, soil saturation) overcome those resisting motion (e.g., soil shear strength; BISSON *et alii,* 2002; ZANCHETTA *et alii,* 2003). Therefore, debris flow initiation is usually favoured by a negative value of curvature (concave topography) whereas the flat and convex surfaces described by curvature values equal and greater than zero do not favour the failure of the volcaniclastic cover of hillslope.

Volcanic Parameters

– Fallout deposit thickness (FT - fig. 2d)

The presence of a volcaniclastic cover is a necessary condition for the possible initiation of volcaniclastic flows during or after heavy and persistent rainfalls. For this reason, the dispersion of fallout deposits related to the main eruptions of Somma-Vesuvius volcano occurred during last 22 ky (BISSON *et alii*, 2007a) has been taken into account. The cumulative thickness of fallout deposits has been reconstructed starting from isopachs and measured points derived from literature data and from geo-referenced stratigraphic sections (tab. 3). For each eruption, these data were transformed into a digital format (point and line layers) containing information on the thickness (expressed in cm), processed using a linear interpolation (TIN) and then stored in a matrix format. Merging the matrices of all eruptions, we have obtained as final output a grid where each cell (size of 10 m) contains the cumulative fallout deposit thickness expressed in cm (fig. 2d). Subsequently, the average thickness of fallout deposit has been calculated for each drainage basin and reported in the relative database (tab. 2).

TABLE 3

List of the main volcanic eruptions occurred in the last 22,000 years.

Volcanic Eruption	Dispersion axis direction	Section map
1906	50° NE	Arrighi et al. 2001
1822	140° SE	Arrighi et al. 2001
1730	110° E	Arrighi et al. 2001
1723	100° E	Arrighi et al. 2001
1707	110° E	Arrighi et al. 2001
1682	65° NE	Arrighi et al. 2001
1631	85° E	Rosi et al. 1993
472.AD	75° E	Sulpizio et al. 2005
79.AD	140° SE	Sigurdsson et al. 1985
A.P.	80° E	Andronico et al. 2002
Avellino 3780 B.P.	60° E	Cioni et al. 2002
Mercato 8010 B.P.	85° E	Zanchetta et al. 2004b
Verdoline 16.000 B.P.	70° E	Cioni et al. 2003
Pomici di Base 18.000 B.P.	80° E	Bertagnini et al. 1998

Geological Parameters

– Lithology (LITH - fig. 2e)

A vector dataset has been obtained from the original geological map at the scale 1:25,000 (185, 196, 197 sheets of the Geological National Survey map). It consists of 134 polygon features that identify the geological formations described by the legend of the original sheets grouped in 8 different typologies based on expected contribution of loose debris: recent alluvial deposits (a), Holocene and Upper Pleistocene volcaniclastic deposits mixed with debris and colluvial deposits (Pv), Pleistocene volcanic deposits (Tv), Quaternary conglomerates and breccia (Q), Oligocene clay shale (Ol2), Cretaceous limestone succession (Crt), Jurassic limestones and dolomia (Giur) and Triassic marly-limestone-dolomia succession (Trias). This information was inserted in the database of drainage basins specifying for each basin the various lithologies (tab. 2).

– Faults and fracture system (FS - fig. 2f)

A vector dataset has been obtained acquiring the faults from the original survey geological map at the scale 1:25,000 (185, 196, 197 sheets of Geological National Sur-

TABLE 4

Weights and indexes assigned to parameters and relative classes, respectively. For the abbreviation used for the classes of lithology and land use see the text.

Parameters	Code	Weights	Classes	Index of classes	Contribution to instability for debris flow triggering
Slope	SL	3	> 28°	3	high
			15° - 28°	2	moderate
			< 15 °	1	low
Basin shape factor	BSF	2	> 1.2	3	high
			1.2 - 0.6	2	moderate
			< 0.6	1	low
Curvature	CURV	1	< -0.001	3	high
			-0.001 - 0.001	2	moderate
			> 0. 001	1	low
Lithology	LITH	1	pv, tv	3	high
			ol2, crt, giur, trias	2	moderate
			a, q	1	low
Faults and fracture system	FS	1	> 3	3	high
			2 - 3	2	moderate
			< 2	1	low
Water table formation	WTF	2	high probability	3	high
			moderate probability	2	moderate
			low probability	1	low
Fallout deposit thickness	FT	3	> 100 cm	3	high
			30 - 100 cm	2	moderate
			< 30 cm	1	low
Land Use	LU	2	zb, zedc, zicrc	3	high
			zav, zv, zu	2	moderate
			cp, s, za	1	low

vey map). The dataset consists of 166 vector line elements describing the main typologies of fault (direct and reverse) and the relative lengths that range from a minimum of 130 meters to a maximum of 5870 meters. Subsequently, the number of faults individuated in each drainage basin was reported in the relative database (tab. 2).

– Water table formation (WTF - fig. 2g)

The WTF parameter describes the probability of water table formation between the bedrock and the volcaniclastic cover. It was defined analysing the type of lithological contact between the fallout deposit and the bedrock including also the possibility of incoming water from the bedrock. In detail, we classified the 8 lithological typologies, the faults and fracture system and the thickness of the debris and volcaniclastic covers on the base of their permeability. For each basin the contrast in permeability between the lithologies and the faults has been evaluated on the base of the different permeability of the bedrock formations, obtained by literature data. Higher is the permeability contrast more probable is the water table formation, and this reflects in a less amount of rainfall necessary for volcaniclastic flow triggering.

This information was inserted in the thematic layer of drainage basins (tab. 2) specifying the degree of probability (low, moderate and high) according to the characteristics above exposed and observed in each basin. The WTF of each drainage basin is visualized in the fig. 2 through a point thematic layer where each point (geometric barycentre of drainage basin) is coloured according the 3 classes of probability above mentioned.

Land Use Parameter

– Land Use (LU - fig. 2h)

The LU layer was obtained digitalizing the CORINE Land Cover (year 2006, 1:100.000 scale) and simplifying the legend into 9 classes: CP (Permanent Cultivation), S (sowable land), ZA (varied agricultural zones), ZAV (open areas with rare vegetation), ZB (forested areas), ZV (zones with shrub and/or herbage), ZEDC (mining, caving and dumping zones), ZICRC (industrial, trading and communication areas), ZU (urban areas). The vector polygon dataset consists of 183 features. Also in this case, the type of land use characterizing each drainage basin was reported in the alphanumerical database associated to the thematic layer of basins (tab. 2).

DETERMINING THE VFSI

With the aim to define the proneness of each drainage basin to generate volcaniclastic flows, we combined the 8 weighted parameters (thematic layers) and indexes, as detailed in the next subsection. It results in building an equation that assigns to each drainage basin a numerical value defined as Volcaniclastic Flow Susceptibility Index (VFSI) and calculated as follows:

$$VFSI = \sum_n (W_n \times I_n) = W_{sl}I_{SL} + W_{curv}I_{Curv} + W_{bsf}I_{BSF} + + W_{lith}I_{LITH} + W_{fs}I_{FS} + W_{wtf}I_{WTF} + W_{ft}I_{FT} + W_{lu}I_{LU}$$

In this equation each parameter n is defined through the weight and the index having the following meanings. The weights (W_{sl},W_{curv},W_{bsf},W_{lith},W_{fs}, W_{wtf}, W_{ft} and W_{lu}) quantify the relative influence of the single parameter, varying from 1 to 3 (1 minimum, 3 maximum). Each parameter is combined with indexes (I_{SL}, I_{CURV}, I_{BSF}, I_{LITH}, I_{FS}, I_{WTF}, I_{FT} and I_{LU}), varying from 1 to 3 in value, which quantify the relevance

ATTRIBUTION OF WEIGHTS AND INDEXES TO EACH PARAMETER

For each parameter, the values assigned to weights and indexes have been defined according to literature data and field survey.

In this study we identify the *slope* of terrain (*SL*) and the *volcaniclastic cover* (*FT*) as the most important parameters (high weight) because the absence of volcaniclastic material and/or the presence of flat areas prevent the initiation of volcaniclastic flows. For this reason we assign a weight equal to 3 to both parameters (see tab. 4). The classes of the SL and the relative indexes have been defined under the assumption that drainage basins with average slope steeper than 25°-28° surely contain areas very prone to generate soil slips (DE RISO *et alii,* 1999; CALCATERRA *et alii,* 1999, 2000; PARESCHI *et alii,* 2000, 2002; ZANCHETTA *et alii,* 2004a). The average slope around 15° has been considered as the lower thresholds for volcaniclastic flow triggering (e.g. BISSON *et alii,* 2010). For these reasons we have assigned values of 3,

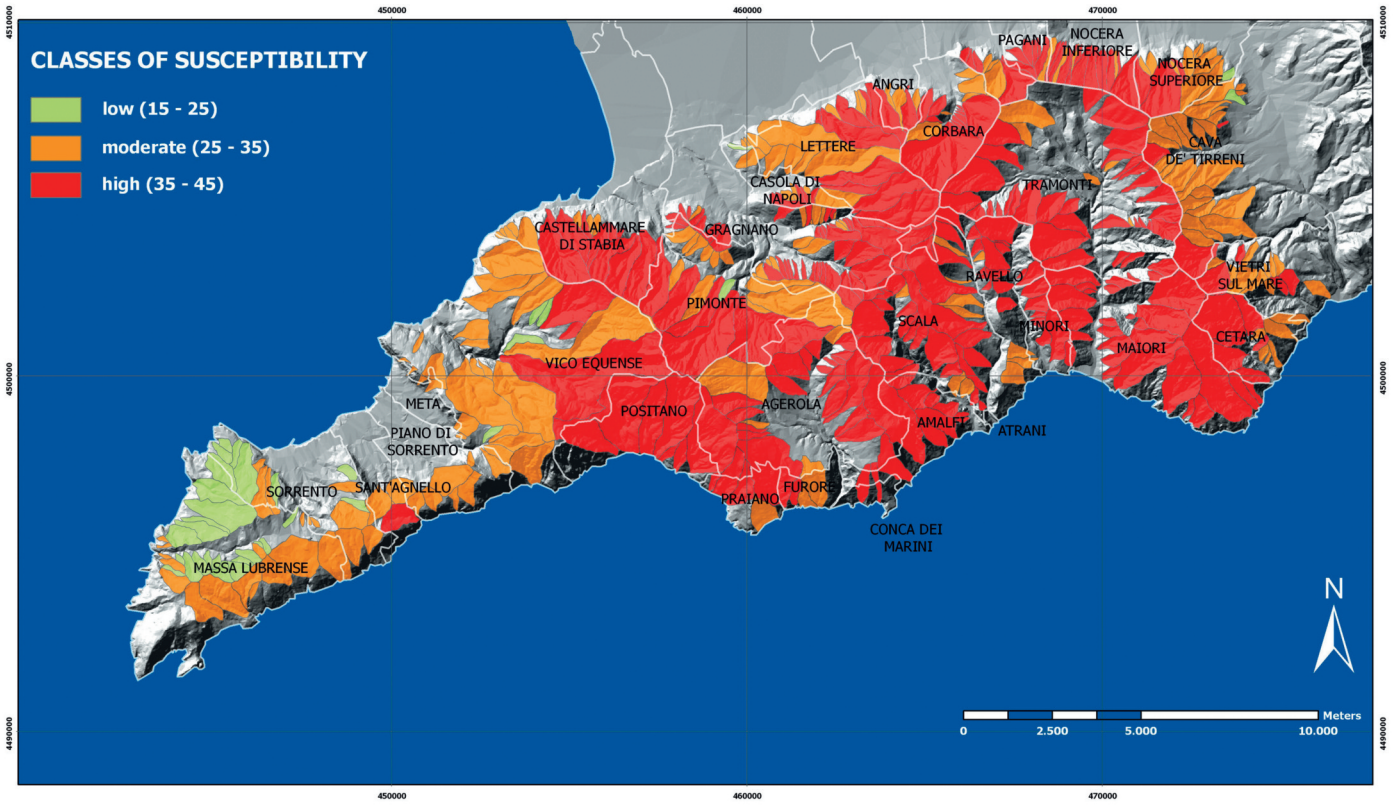

Fig. 3 - VFS Index Map. The white outlines identify the administrative boundaries of the municipalities.

2 and 1 to average slopes steeper than 28°, between 15° and 28°, and lower than 15°, respectively (tab. 4).

The classes of the *FT* parameter (tab. 4) are defined by thresholds of thickness equal to 100 cm and 30 cm, respectively for a high or intermediate contribution to volcaniclastic flow generation. These values are in agreement with some studies about the volcanic hazard at Somma-Vesuvius carried out in collaboration with the Italian Department of Civil Protection (Mazzarini & Bisson, 2008).

Parameters considered important but not prominent (moderate weight) for volcaniclastic flow generation are the shape of drainage basin (*BSF*) and the probability of water table formation (*WTF*) between the bedrock and the volcaniclastic covers. Even if these parameters are not crucial, some classes of them (tab. 4) can provide an important contribution to volcaniclastic flow generation. Previous studies about BSF (Pareschi *et alii*, 2000) individuate the value of 1.2 and 0.6 as thresholds for high and intermediate probability of volcaniclastic flow generation (tab. 4).

The WTF index (tab. 4) derives from the occurrence of contrast of permeability in each drainage basin (general permeability of the lithology, probable presence of springs, high water table level in the bedrock). The classes of the WTF are defined from high probability to low probability on the base of the prevalence in the basin of a low or high permeable bedrock and of the number and discharge of the springs present in each basin.

The last parameters analysed in this study are the *curvature* (*CURV*), the *lithology* (*LITH*), the *faults and fracture system* (*FS*) and the *land use* (*LU*). These parameters play a minor role and therefore are characterised by lower weights, and were ranked into 3 classes.

For the *curvature* parameter, the maximum value has been assigned to concave areas, whereas intermediate and low values characterise flat and convex areas, respectively (tab. 4).

For the *lithology*, the attribution of the indexes were based on litho-technical characteristics, in particular we have considered the attitude of each lithology to produce loose debris, as observed and estimated during fieldwork in areas surrounding the Sorrentina Peninsula. In drainage basins with more than one lithology, the value of the index has been calculated weighting the contributions of the different lithologies

The *faults and fracture system* parameter was classified attributing the indexes according to the number of the faults that affect the bedrock units in each drainage basin and considering their lengths; in fact, the amount of the debris material increases according to the fault length (Fubelli *et alii*, 2008; Leoni *et alii*, 2009). The index value is also related to the relevance and length of the fault under the assumption that more the fault gives a big displacement more the fractured zone is large.

The indexes of the *land use* parameter (tab. 4) have been defined basing on the thickness of soil related to the type of land use, and taking into consideration if they are under maintenance or wild. The indexes are the same used in Leoni *et alii* (2009) and (in press). In drainage basins with more than one land use, the value of the index has been calculated weighting the contributions of the different land uses.

The VFSI has been tested on the 35 drainage basins that triggered the debris flows occurred on May 1998 in Sarno Quindici area. The test shows that 32 out of 35 basins are classified as high susceptibility areas.

TABLE 5

For each municipality, the number of drainage basins classified for VFSI is reported.

Municipality	Number of drainage basins			
	low VFSI	*moderate VFSI*	*high VFSI*	*total*
agerola	0	3	21	24
amalfi	0	0	12	12
angri	0	3	2	5
casola di napoli	1	4	5	10
castellamare di stabia	0	8	9	17
cava de tirreni	1	23	3	27
cetara	0	5	6	11
corbara	0	5	11	16
furore	0	2	1	3
gragnano	0	14	34	48
lettere	0	12	9	21
maiori	0	0	26	26
massa lubrense	19	14	0	33
meta	0	2	0	2
minori	0	0	7	7
nocera inferiore	0	3	12	15
nocera superiore	1	9	3	13
pagani	0	1	6	7
piano di sorrento	0	7	0	7
pimonte	1	11	6	18
positano	0	0	6	6
praiano	0	1	3	4
ravello	0	4	15	19
santagnello	0	2	1	3
santegidio del monte albino	0	3	4	7
scala	0	7	22	29
sorrento	7	9	0	16
tramonti	0	5	34	39
vico equense	4	21	3	28
vietri sul mare	0	11	4	15

RESULTS AND DISCUSSION

The map obtained applying the VFSI equation to the drainage basins of the Sorrentina Peninsula distinguishes the 488 drainage basins according to three different classes of susceptibility for triggering volcaniclastic flows: low (VFSI ≤ 25), moderate (25 < VFSI < 35) and high (VFSI ≥ 35; fig. 3). The thresholds of classes have been defined dividing in 3 equal intervals the range between the maximum and minimum value (45 and 15, respectively) obtained from the VFSI equation fig. 3 shows that 265 basins classify as high, 189 as moderate and only 34 as low susceptible areas. This highlights how about 55% of studied drainage basins have high proneness for volcaniclastic flow triggering, occurring prevalently the central and eastern part of the Sorrentina Peninsula (fig. 3). The drainage basins with low proneness are mainly located in the western part of the Sorrentina Peninsula, involving mainly the municipalities of Massa Lubrense and Sorrento (fig. 3). A more specific analysis about the spatial distribution of drainage basins allowed the ranking of the municipalities to their proneness to generate volcaniclastic flows. Tab. 5 reports for each municipality the number of drainage basins according to the classes of VFSI (low, moderate and high).

The diagram of fig. 4 highlights three main groups of municipalities. The first group consists of 7 municipalities where more than 85% of the basins are classified with high VSFI. In particular, for Amalfi, Maiori, Minori, and Positano municipalities the percentage reaches the maximum (100%). The second group (10 municipalities) shows less than 85% of drainage basins classified with high VFSI, while the third group (12 municipalities) is defined by a preponderance of drainage basins with moderate VFSI. Only one municipality (Massa Lubrense) contains drainage basins with prevalent low VFSI. In addition, we can observe how the municipalities with the highest number of historical records of volcaniclastic flows contains the greater number of drainage basins classified as high susceptibility areas (e.g. Maiori).

This zonation indicates how the Sorrentina Peninsula can be considered an area strongly prone to generation of volcaniclastic flows.

CONCLUSION

The GIS based approach here presented combines morphometric analysis derived from Digital Elevation Model with volcanological, geological and land use information to investigate the volcaniclastic flow generation

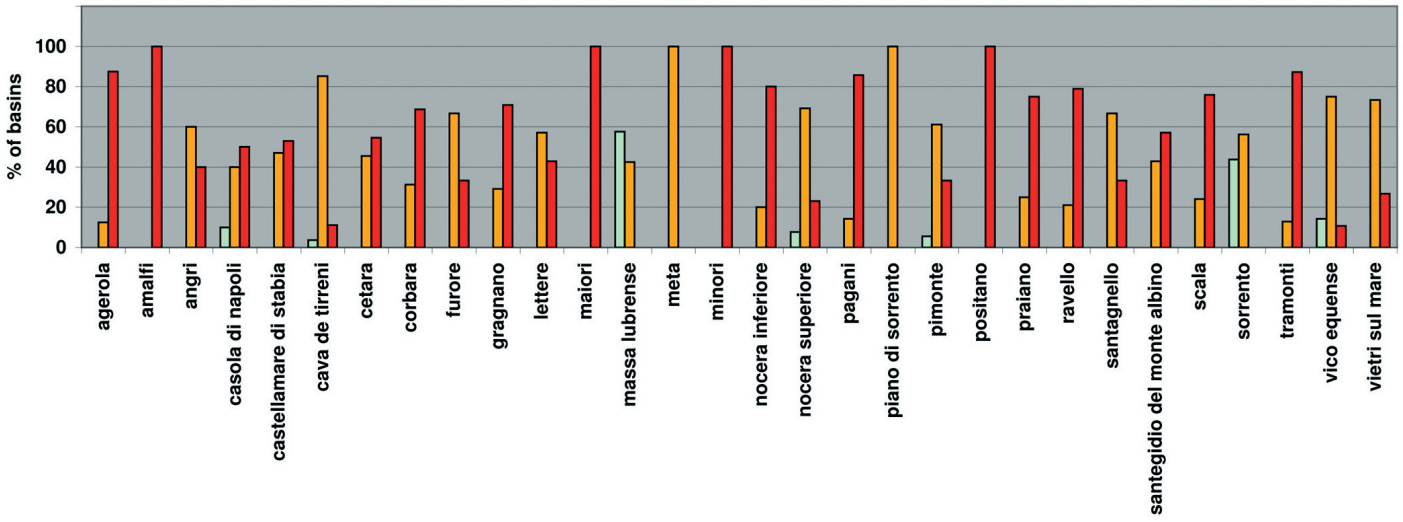

Fig. 4 - Drainage basins classified for VSFI (red - high class, orange - moderate class, light green - low class) and expressed as % for each municipality.

proneness in volcanic areas. As result we propose an Index (VFSI) for estimating the areas more prone to volcaniclastic flows generation. This method, validated in the Sarno-Quindici area, allowed to zone the drainage basins of the Sorrentina Peninsula, and identifying areas characterised by three different classes of susceptibility (low, moderate and high). The municipalities that could be subjected to the highest probability for volcaniclastic flow triggering have also been delineated. Of the 488 studied drainage basins 55% belong to the high class of volcaniclastic flow proneness, 38% to the moderate and 7% to the low. These results confirm that the study area can be strongly affected by volcaniclastic flow generation during both inter-eruptive and syn-eruptive times. In addition, some municipalities show all drainage basins belonging to the class of high proneness for volcaniclastic flow generation. This indicates how these municipalities deserve a constant and detailed monitoring activity, in order to mitigate the volcaniclastic flow hazard.

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