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Volcanic hazard at Vesuvius: An analysis for the revision of the current emergency plan

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ABSTRACT

Mt Somma-Vesuvius is a composite volcano on the southern margin of the Campanian Plain which has been active since 39 ka BP and which poses a hazard and risk for the people living around its base. The volcano last erupted in 1944, and since this date has been in repose. As the level of volcanic risk perception is very high in the scientific community, in 1995 a hazard and risk evaluation, and evacuation plan, was published by the Italian Department of Civil Protection (*Dipartimento della Protezione Civile*). The plan considered the response to a worst-case scenario, taken to be a subplinian eruption on the scale of the 1631 AD eruption, and based on a volcanological reconstruction of this eruption, assumes that a future eruption will be preceded by about two weeks of ground uplift at the volcano's summit, and about one week of locally perceptible seismic activity. Moreover, by analogy with the 1631 events, the plan assumes that ash fall and pyroclastic flow should be recognized as the primary volcanic hazard. To design the response to this subplinian eruption, the emergency plan divided the Somma-Vesuvius region into three hazard zones affected by pyroclastic flows (Red Zone), tephra fall (Yellow and Green Zone), and floods (Blue Zone). The plan at present is the subject of much controversy, and, in our opinion, several assumptions need to be modified according to the following arguments: a) For the precursory unrest problem, recent scientific studies show that at present neither forecast capability is realistic, so that the assumption that a future eruption will be preceded by about two weeks of forecasts need to be modified; b) Regarding the exposure of the Vesuvius region to flow phenomena, the Red Zone presents much inconsistency near the outer border as it has been defined by the administrative limits of the eighteen municipality area lying on the volcano. As this outer limit shows no uniformity, a pressing need exists to define appropriately the flow hazard zone, since there are some important public structures not considered in the current Red Zone that could be exposed to flow risk; c) Modern wind records clearly indicate that at the time of a future eruption winds could blow not only from the west, but also from the east, so that the Yellow Zone (the area with the potential to be affected by significant tephra fall deposits) must be redefined. As a result the relationship between the Yellow Zone and Green Zone (the area within and beyond which the impact of tephra fall is expected to be insignificant) must be reconsidered mainly in the Naples area; d) The May 1998 landslide, caused in the Apennine region east of the volcano by continuous rain fall, led to the definition of a zone affected by re-mobilisation of tephra (Blue Zone), confined in the Nola valley. However, as described in the 1631 chronicles of the eruption, if generation of debris flows occurs during and after a future eruption, a much wider region east of the Somma-Vesuvius must be affected by events of this type.

1. Introduction

Vesuvius is one of the most famous volcanoes in the world and supports a population of some 600,000 people all around its base. In 1995 a hazard and risk evaluation and an evacuation plan was published by the Dipartimento della Protezione Civile (1995). The original plan considered the response to a worst-case scenario, taken to be a subplinian eruption on the scale of the 1631 event, and based on a volcanological reconstruction of this eruption (Rolandi et al., 1993c; Rosi et al., 1993), ash fall and pyroclastic flow have been recognized as the primary volcanic hazards. The 1631 eruption ended 500 years of quiescence and appears to have been preceded by about two weeks of ground uplift at the volcano's summit and about one week of felt local seismicity. By analogy with these events, the emergency plan assumed that it would be possible to initiate evacuation of the volcano at least two weeks ahead of the eruption. This time interval is significant because of its potential influence on the view of local decision makers on scientist's ability to forecast volcanic eruptions. The plan and its scientific considerations have been the subject of much controversy, both within the Italian volcanological community and among people living all around the volcano, so that a pressing need exists to develop

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an appropriate discussion about the problems that could be addressed in a revision of the emergency plan. The results published in a previous paper (Solana et al., 2008) clearly showed that the understanding of civil authorities on to respond during an emergency is incomplete. The purpose of this paper is to address other basic questions regarding the hazard and risk of a future eruption, and we hope that both the arguments contained in the previous work and in this paper will be strong enough to overcome the prejudices persisting in the administrative authorities and persuade all readers to accept new indications for future revision of the emergency plan.

2. Eruptive history of Somma-Vesuvius

Somma-Vesuvius has undergone several changes in style of activity during its volcanological life. From 39,000 to 25,000 years BP it was essentially an effusive volcano (Somma), and from 25,000 BP to AD 1631 activity was dominated by eight Plinian eruptions (Santacroce, 1987). Starting from the prehistoric eruption of Avellino (Lirer et al., 1973; Rolandi et al., 1993b), the Plinian events were regularly followed by interplinians, moderately explosive–effusive activities, separated by repose intervals of hundreds of years from the successive Plinian eruption (Rolandi et al., 1998). The long-lived mediaeval interplinian activity, starting after the AD 472 Plinian eruption (Rolandi et al., 2004), and ending in the 1139 event, was responsible for the construction of a new edifice (Vesuvius), nested in the Somma caldera. During the modern historic age, soon after the 1631 eruption, Vesuvius has been again largely effusive during its last interplinian phase, which takes the form of an alternation of the so-called "Vesuvuan Cycle" into which persistent activity was organized from 1631 to 1944 (Pesce and Rolandi, 1994), with occasional strombolian eruptions (VEI = 1–2) and effusive activity.

3. Tephra fall and pyroclastic currents from the past Plinian eruptions at Somma-Vesuvius

During Plinian eruptions, wide ranges of volumes (Rolandi et al., 1993a,b,c; Cioni et al., 1999, 2003; Rolandi et al., 2004) (Table 1) and tephra compositions (Ayuso et al., 1998) have been erupted, long before the AD 472 eruption from Somma, and after the AD 472 eruption from Vesuvius, producing many lobe-shaped tephra deposits. Fig. 1A represents the orientation and width of Plinian tephra lobes, each consisting of air-fall tephra 10 cm thick from a single event. In Fig. 1B dispersal data are arranged to highlight the direction of dispersion of past tephra fall deposits taking into account the maximum percentage of any sector covered by the 10 cm isopach. Six Plinian eruptions (no. 2—17 ka BP; no. 3—16 ka BP; no. 4—8 ka BP; no. 5—3.55 ka BP; no. 7—AD 472; and no. 8—AD 1631) are shown to have occurred during periods of northeast–east winds producing thick bands of tephra extending far downwind from the volcano. Exceptions are the events showing east–southeast dispersion (no. 1—25 ka BP, and no. 6—AD 79) (Lirer et al., 1973; Sigurdsson et al., 1985; Rolandi et al., 2007). Each of the Plinian eruptions gave rise to flow phases (pyroclastic flows, surges, debris flows and floods) whose deposits are distributed all around the volcano. Large pyroclastic flow and volcaniclastic debris-flow deposits are associated with the 18 and 8 ka Plinian events of Somma (Arnò et al., 1987; Rolandi et al., 1993a), whose products are well exposed from the northwest to northeast sides of the volcano, covering an area of more than 150 km^2. The grain size characters of the flow deposits suggest they were emplaced as matrix-supported currents with low turbulence (Rolandi et al., 1993a; Gurioli et al., 2005). In the prehistoric age (3.55 ka) a proximal volcaniclastic debris flow and a very relevant pyroclastic surge sequence occurred during the magmatic phase of the Avellino eruption (Lirer et al., 1973; Rolandi et al., 1993b). Late, very impressive, surge currents were emplaced mostly toward the north to northwest sectors of Somma, covering an area of more than 500 km^2 (Figs. 2, 3A). Important pyroclastic flow, volcaniclastic debris flow and surge sequences are also associated with the AD 79 eruption (Sigurdsson et al., 1985) (Figs. 2, 3B). Surge and pyroclastic flow units buried the town of Herculaneum under 20 m of pyroclastic deposits. Pyroclastic flow deposits of the AD 79 eruption are well exposed from the southwest (S. Giorgio a Cremano), to the south (Ercolano-Torre del Greco), and to the southeast (Torre del Greco-Pompei-Boscotrecase) (Fig. 2). We do not recognize important AD 79 flow deposits on the northern slopes of Somma (i.e. from Pollena to the Somma Vesuviana district). Surge and accretionary lapilli beds constituted the upper part of the AD 79 deposits (Fig. 3C) bearing evidence that important later surge currents were formed by a large number of small phreatomagmatic to phreatic explosions (Sigurdsson et al., 1985). The AD 79 late surge extended within 10–12 km from the volcano, mainly toward the southeast (Fig. 2). The AD 472 Plinian eruption generated block and ash flow nueé ardentes, and volcaniclastic debris flows (Fig. 3D) which interrupted the final fall phase. (Rolandi et al., 2004). As in the AD 79 eruption, late surge activity also occurred for the AD 472 eruption, with deposits extending 10 km from the east of the summit (Figs. 2, 3E). The 1631 eruption, the first event of Vesuvius with a Plinian character, has been reconstructed in detail from historic documents (Braccini, 1632; Rolandi, 1991), and both field evidences and historical reports clearly indicate the development of a flow phase from the interruption of a Plinian column (Figs. 2, 3F). The historical eruptions (AD 79, AD 472, AD 1631) were also accompanied by conspicuous debris flows and floods that, by analogy with the pyroclastic flow density currents, were emplaced in the paleovalleys around the Somma-Vesuvius (Figs. 2, 3G, H).

4. Hazard evaluation at Vesuvius: The emergency plan of the Italian Civil Protection

The original plan published for Vesuvius (Dipartimento della Protezione Civile, 1995) considered the response to a worst-case scenario, taken to be a subplinian eruption on the scale of that of 1631 and based on a volcanological reconstruction present in the literature

Table 1
Confirmed Plinian and subplinian eruptions from Somma-Vesuvius. The volumes estimated for the Ottaviano, Avellino and AD 79 (Pompeii) eruptions consider both flow and fall deposits.

Name (Alternative names in brackets)	Date (Years before 2009)	Deposited volume DRE (km^3)	Reference
Codola	25,000	1	Rolandi (unpublished data)
Sarno (Basal)	17,000	1.60	Bertagnini et al. (1998)
Novelle (Greenish)	15,000	0.25	Cioni et al. (2003)
Ottaviano (Mercato)	8400	0.61	Rolandi et al. (1993a,b,c)
Avellino	3500	1.00	Rolandi et al. (1993a,b,c)
Pompei	1920 (AD 79)	4.00	Sigurdsson et al. (1985)
Pollena	1537 (AD 472)	0.55	Rolandi et al. (2004)
1631	378 (AD 1631)	0.55	Rolandi et al. (1993a,b,c)

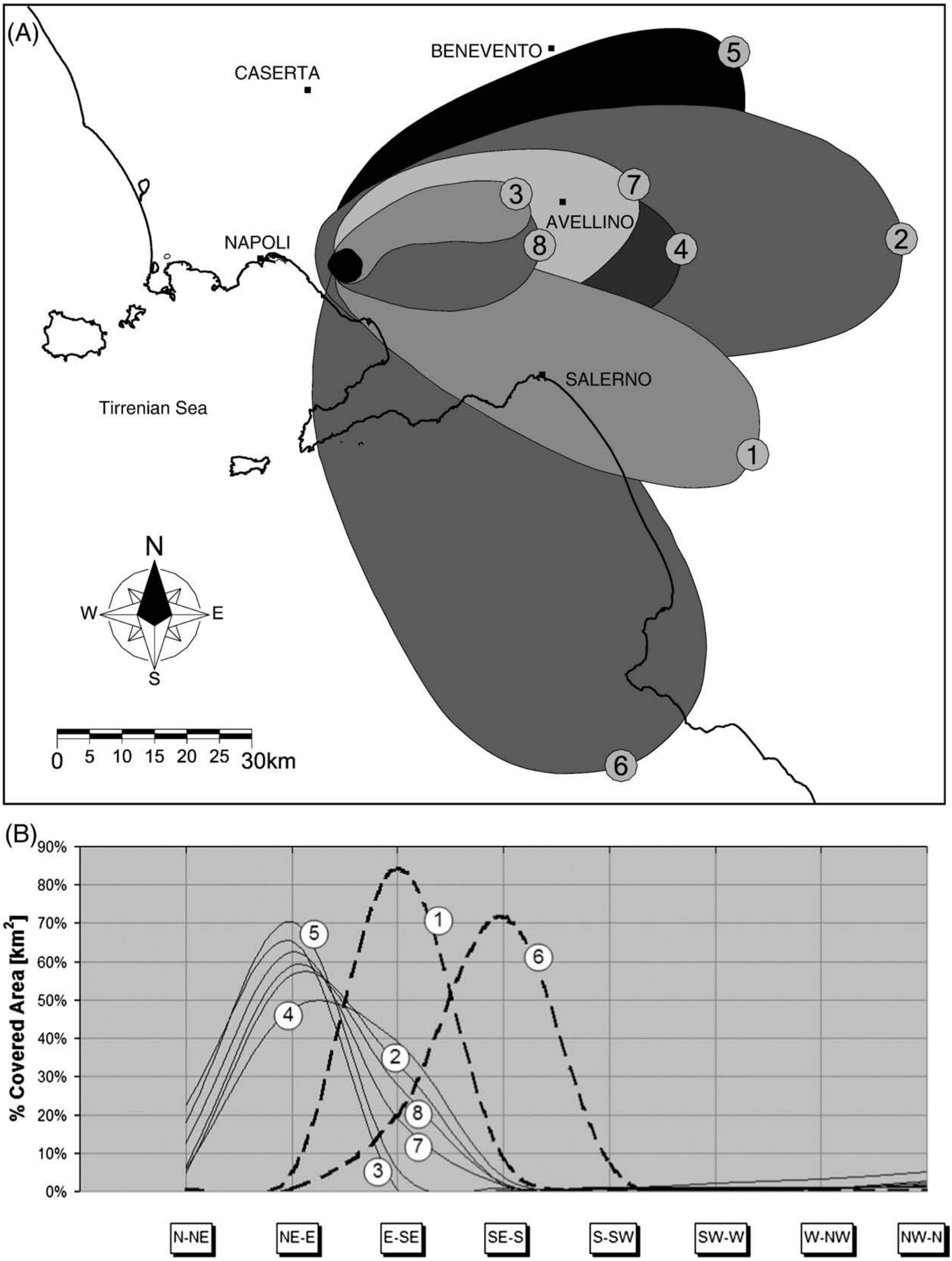

Fig. 1. (A) Distribution map of pyroclastic fall products of the Somma-Vesuvius deposited in the last 25 ka BP. Each lobe consists of 10 cm thick air-fall tephra from a single Plinian eruption. Numbers are arranged according to the chronological sequence of the eruptions in the last 25 ka. Field data are from: Rolandi (unpublished data) (1), (2), (3); Rolandi et al. (1993a,b) (4), (5); Sigurdsson et al. (1985) (6); Rolandi et al., 2004 (7), 1993a,b,c (8); (B) Data arranged to highlight the direction of maximum fall dispersion trough the percentage of the sectors covered by 10 cm isopachs.

(Rolandi et al., 1993c; Rosi et al., 1993), which recognized tephra fall and pyroclastic flows as primary volcanic hazards. The 1631 eruption ended about 500 years of quiescence, and appears to have been preceded by about two weeks of ground uplift at the volcano's summit and about one week of locally perceptible seismic activity (Rolandi, 1991; Rolandi et al., 1993c). The precursory unrest led to a spontaneous

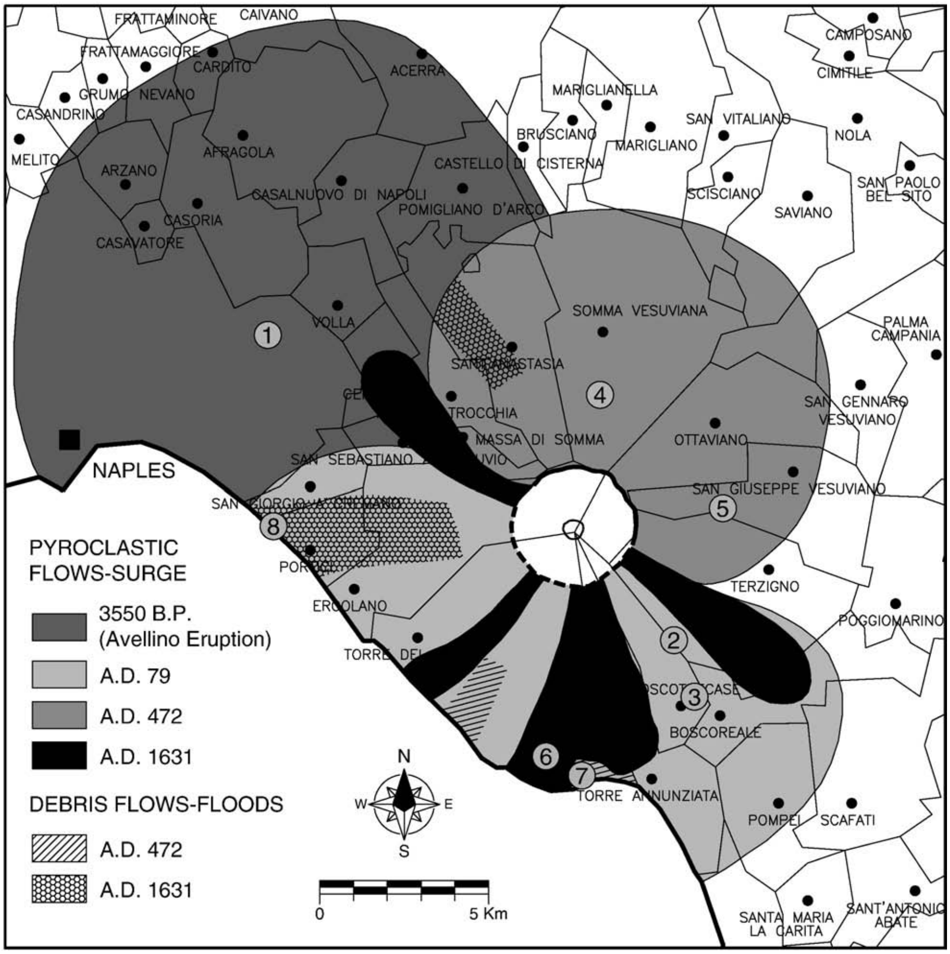

Fig. 2. Map showing a representation originated by extended unpublished fieldwork of pyroclastic flows and base surge deposits for prehistoric and historic Plinian eruptions of the Somma-Vesuvius. Historical floods and debris flows are also shown. The outer limit of the areas coincides with the deposits of 50–100 cm thickness. Numbers indicate locality of flow outcrops shown in Fig. 3.

evacuation of some 40,000 people, but the eruption claimed about 6000 victims. To design the response to a subplinian eruption, the emergency plan divided the Somma-Vesuvius area and the surrounding region into hazard zones according to their exposure to pyroclastic flows, tephra falls, and floods in the eastern distal area of the volcano (Fig. 4):

1- the *Red Zone* is potentially to be affected by pyroclastic flow and tephra fall;
2- the *Yellow Zone* lies beyond the range of pyroclastic flows, but is potentially to be affected by significant tephra fall deposits;
3- the *Green Zone* extends beyond the limits of significant tephra fall;
4- the *Blue Zone* shares the characteristics of the Yellow Zone, with the addition of pyroclastic debris flow and flood hazards.

Having defined the four hazard zones, the plan established an eight-level scheme for responding to different stages of an emergency, from initial unrest to post-eruption conditions (see Table 2). By analogy with the 1631 eruption, the emergency plan assumed that it would be possible to initiate evacuation of the area immediately around the volcano at least two weeks ahead of an eruption, corresponding with the *Risk Level 4* (see Table 2).

5. An analysis of the emergency plan by the Italian Civil Protection: Comparison and recommendations

Comparative analyses between the eruptive history of Somma-Vesuvius, the volcanic hazard models presented in this paper, and the hazard evaluation included in the emergency plan of the Italian Civil Protection (1995), highlight several potential problems concerning the perception of a future crisis by focussing on the 1631 eruption scenario adopted by authorities (Chester et al., 2002). Some of these problems are now discussed in the following sections.

5.1. Predicting a future eruption on Vesuvius

The historical record of frequent eruptions at Somma-Vesuvius implies the inevitability of another eruption (Crandell and Mullineaux, 1978). However, the criteria for recognising whether the volcano has had, in the 1944 event, its last eruption, and successively will become extinct, or will erupt at the end of a short or long repose period, are unknowable. No volcanic activity has been recorded since 1944, and so it may be hypothesized that Somma-Vesuvius is in the

Fig. 3. Flow deposits from prehistoric and historic eruptions as seen in the areas of Fig. 2: (A) surge deposit of 3.55 ka B.P. Avellino eruption, in Arpino (Casoria), about 12 km north of the summit of the Vesuvius. Note the Sannitic tombs dated IV century B.C. excavated in the surge deposit; (B) Volcaniclastic debris-flow deposit from AD 79 eruption in the Pozzelle quarry, about 6.5 km south–east of Vesuvius cone summit; (C) Late Surge deposit of AD 79 eruption at Boscotrecase, about 6 km south–east of Vesuvius cone summit; (D) Volcaniclastic debris-flow deposit from AD 472 eruption at Somma Vesuviana, about 4 km southeast of Vesuvius cone summit; (E) Late Surge deposit of AD 472 eruption in the S. Giuseppe Vesuviano, about 6 km east of Vesuvius cone summit; (F) Pyroclastic flow deposit of AD 1631 eruption at Villa Inglese quarry (Torre del Greco), about 7 km south from the Vesuvius summit. Flow deposit underlie the 1760 lava flow of Vesuvius modern historic interplinian activity; (G) Flood deposits of AD 472 eruption at Torre Annunziata, about 7.5 km south–southeast from the Vesuvius summit; (H) Debris-flow deposits of AD 1631 eruption at S. Giorgio a Cremano (Pietrarsa locality), about 9 km southwest from the Vesuvius summit.


(A)
(B)
(C)
(D)
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(H)

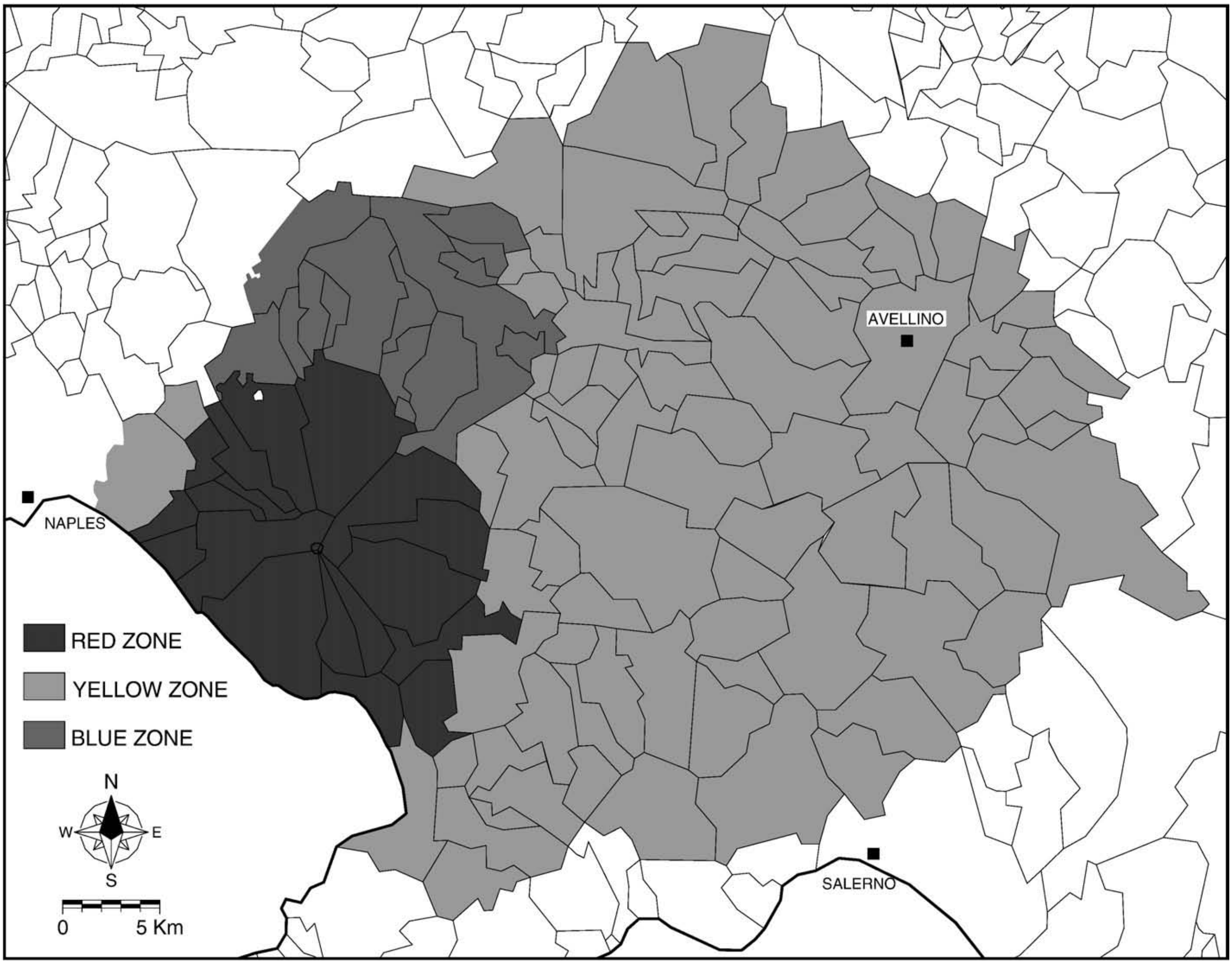


Fig. 4. Hazard zones of the Civil Protection Emergency Plan: *Red Zone*, with the potential to be affected by pyroclastic flows and ash fall, *Yellow Zone*, with the potential to be affected by significant ash fall., *Blue Zone*, is the area affected by tephra fall with characters of the Yellow Zone, and by pyroclastic debris flow and floods.

repose phase which normally occurs after the interplinian phase (Rolandi et al., 1998). Owing to this, Vesuvius may now be in a closed vent condition, but when the next eruption will occur is still a matter of conjecture, as at present no forecasting capability is realistic (Kilburn, 2003; Solana et al., 2008). Uncertainty remains as to the style of a future eruption, but issuing emergency forecasts in terms of probabilities should take account of the fact that a future eruption could be more severe than a subplinian event (Marzocchi et al., 2004). Authorities, however, typically take for granted that the next eruption on Vesuvius will be subplinian, and that it will be possible to forecast

Table 2
Alert levels from the Vesuvius emergency response plan.

Risk level	Alert	Behaviour of volcano	Emergency response
0	No alert	Daily behaviour typical for repose during previous 20 years. All monitoring signals at background levels.	No action required.
1	1st-level warning	Values from one monitoring signal exceed background level.	Change in signal made public as factual statement.
2	2nd-level warning	Values from one monitoring signal continue to increase above background level. The sustained increase suggests possible reawakening of volcano.	Permanent monitoring networks supported with additional instruments. Emergency teams put on alert.
3	Initial alarm	Values from more than one monitoring signal are maintained above background levels. The combined increase suggests that the volcano is entering the preparatory phases before eruption.	The Government declares a State of Emergency. Emergency teams are mobilised.
4	Full alarm	Values from several monitoring signals continue to increase. Their acceleration *might* still be reversible.	Evacuation of communities from volcano (the "Red Zone").
5	Eruption imminent	Acceleration in values from monitoring signals irreversible. Eruption is imminent.	Evacuation of all personnel from volcano.
6	Eruption in progress	Eruption in progress	Evacuation is necessary to avoid heavy tephra fall in the Yellow Zone, beyond the volcano.
7	End of eruption	The eruption has ceased. Hazards may still exist from landslides, mud flows and gas emission.	The State of Emergency is rescinded. Populations may return to safe zones.

this eruption weeks ahead of time (Sparks, 2003). It is quite obvious that both assumptions need to be modified.

5.2. The choice of the hazard zones: Criteria and comparisons

5.2.1. Flow hazard zone

To define the flow hazard zone we consider the past history of the Somma-Vesuvius, and assume that actual distances travelled by future flows may be of the same order as those of past flows whose deposits are now discernible in the geologic records (Fig. 2). The distance (*L*) reached by future pyroclastic flow or surges depends on the height (*H*) of the column collapse (Sheridan, 1979; Sheridan and Malin, 1983) and on the presence of topographic barriers on the slopes of the volcano. So the above comparison is reasonable if: a) the topography of the volcano slopes has not changed substantially by time, and, b) the VEI of a future eruption is of the same order as those of the historical eruptions that have generated the flows (AD 79, AD 472, AD 1631). These assumptions are designed to be applicable at Somma-Vesuvius on the basis of geologic mapping (Fig. 2), and a hazard scenario could be constructed from pyroclastic flows at Somma-Vesuvius. Effects of local topography play a substantial role on controls of future flow directions (Newhall and Hoblitt, 2002). Control on flow direction includes several aspects such as local irregularities of the substratum both at small and large scales. Small-scale topographic irregularities could allow rapid deflections of the flow, and rapid transitions in the turbulence regime within the flow (Gurioli et al., 2002), whereas large scale topographic barriers, such as a caldera wall, might be able to direct the flow out toward the opposite edges. From this point of view it is important to consider if future pyroclastic flows and surges will be able to get over the Mt Somma barrier. The northward sector of the Somma caldera wall has worked as a topographically high area in the past: one could quote the example of the prehistoric Avellino eruption, where coarse volcaniclastic debris flows were mostly emplaced in the western and southwestern sectors of the volcano as they were restricted by topographically high area of the Somma wall (Rolandi et al., 1993a,b,c; Milia et al., 2007). In contrast to this, the very mobile, late pyroclastic surge of the same eruption passed over the caldera rim and propagated onto the north-western sector of the Campanian plain (Rolandi et al., 1993a,b,c) (Figs. 2, 3A). For the AD 79 and 1631 eruptions the Somma caldera wall directed the flows mainly out toward the opposite edges restricting the distribution of flows toward the western, southern and eastern sectors (Rossano et al., 1998) (Fig. 2). The most important effusive activity that occurred in the modern historical interplinian phase (1631–1944) has refilled the deep valley between the Somma and Vesuvius (the Somma caldera wall is actually only 300 m high) (Fig. 5), so that very mobile flows of future eruption will easily pass over the Somma caldera rim. According to the above scenario, the future flow pattern will be near symmetrical all around the Somma-Vesuvius, or rather: *If a flow event will occur at Vesuvius, any sector around the volcano will be devastated for a long distance from the summit*. The extent of the outer limits of the flow hazard zones can be placed by using the sector distribution attained by past flows at a distance equal to the longest flow deposit formed by past eruptions of Somma and Vesuvius, and since it is not possible to know in advance the actual direction a flow could take from a future eruption, the following circular combined flow-surge hazard zones can be defined: 1) *Zone 1* with a radius of 11 km drawn from the flow deposits of the historic Plinian eruptions (AD 79, AD 472 and AD 1631) (Fig. 2), filled by about 70% of past pyroclastic flow deposits. The travelling distances reached by pyroclastic currents into sectors of a volcano is an aspect concerning specific levels of event tree models for volcanic crises conceived by Newhall and Hoblitt (2002). These levels for pyroclastic flows associated to eruptions of VEI = 4–5 give empirical probabilities of 50% that the flows reach the distance of 11 km. This zone is considered *the area of potential hazard for density currents* (Fig. 6). The outer part of zone 1, from 8 to 11 km, is less likely to be affected by density currents from a future eruption than its inner part extending from 0 to 8 km. We observe that this inner area is covered by more than 90% by the flow deposits of the historic eruptions. From the above-mentioned arguments, the 0–8 km area of zone 1 must be considered as *the area of greatest potential hazard for pyroclastic density currents* (see also Dobran et al., 1993, 1994; Neri and Dobran, 1994; Rossano et al., 1998; Neri et al., 2003 and references therein). 2) *Zone 2* with a radius of 18 km is defined by considering the extension of the prehistoric flow deposits of the Avellino eruption (Mastrolorenzo et al., 2006), where between 11 and 18 km extends *the area of low potential hazard for pyroclastic density currents* for events characterized by VEI > 5 (Fig. 6). On the basis of the past volcanological history of Somma-Vesuvius, the well-defined role of this zone arises when it is observed that density currents associated with explosive eruptions considerably larger than historical events (VEI > 5) are very unlikely to occur. The working hypothesis of hazard zonation presented in Fig. 6 is based on simple volcanological criteria that refer to the mapping of past flowage events all around the volcano, placed in a circular geometry (Crandell, 1980; Miller, 1980; Crandell et al., 1984; Miller, 1989; Newhall and Hoblitt, 2002), and establish the basic concept that: *the extension of flow hazard is gradational, decreasing radially with increasing distance from the vent*. According to this point of view, we considered the range 8–11 km as playing the role of a reasonable margin of safety for protection from flow risk of people living at the base of the volcano.

Remarking on the potential zone to be affected by pyroclastic flows (The Red Zone), the emergency plan includes all the municipalities (*Comuni*) on the volcano itself (Fig. 4), and the outer limits align perfectly with the administrative municipality limits. In our opinion, the report failed to make an appropriate choice, as it represents the world's only case where the volcanological limits of the flow hazard zone coincide with municipality limits. By comparing the Red Zone (Fig. 4) with the above hazard areas (Fig. 6), we observe that the Red Zone boundaries are very irregular because they coincide with administrative limits, and thus this is the object of several contradictions that will be discussed in detail in the following cases: *a)* The outer Red Zone is less extensive to the east and to the west (the minimum distances from the summit are 8 km and 7 km, respectively), and extends for a major distance to the north and to the southeast (maximum distances from the summit are 10 km, and 12 .km, respectively). Taking such an unusual form, when the Red Zone is compared with the 11 km hazard zone of the present work, the western and eastern borders mark a broad shifting (Fig. 6); *b)* as the outer limit of the Red Zone is to a great extent volcanologically arbitrary, the flow hazard-risk is a maximum inside some portions of the Red Zone, and absent from immediately contiguous areas. We could quote many cases all around the outer limit of the Red Zone where these anomalies occur. One of the most telling is presented in Fig. 7 on the northern slope of Somma-Vesuvius, at the border between the towns Pomigliano and S. Anastasia: the municipality of S. Anastasia is entirely included in the Red Zone, and that of Pomigliano d'Arco in the Blue Zone (Fig. 4). Nevertheless, a narrow area belonging to the Pomigliano d'Arco municipality management is entirely placed in the S. Anastasia municipality, and although it lies in the heart of the Red Zone, it is included in the Blue Zone, as is the rest of Pomigliano town. This is one of many examples existing along the borders of the Red Zone where the administrative limit, playing the role of a volcanological limit, appears as an evident contradiction; **c)** the Red Zone map is extensively used by administrative authorities for planning the land use around the volcano, i.e. a moratorium against building is in effect. We have observed that to the west of the Red Zone, toward Naples municipality, there is a misinterpretation of the areas subject to flow events, as both the 8 and 11-km flow hazard zones show significant shifting from the limits of the current Red Zone (Fig. 6). In this area no careful high risk evaluations have been planned for land use, and the

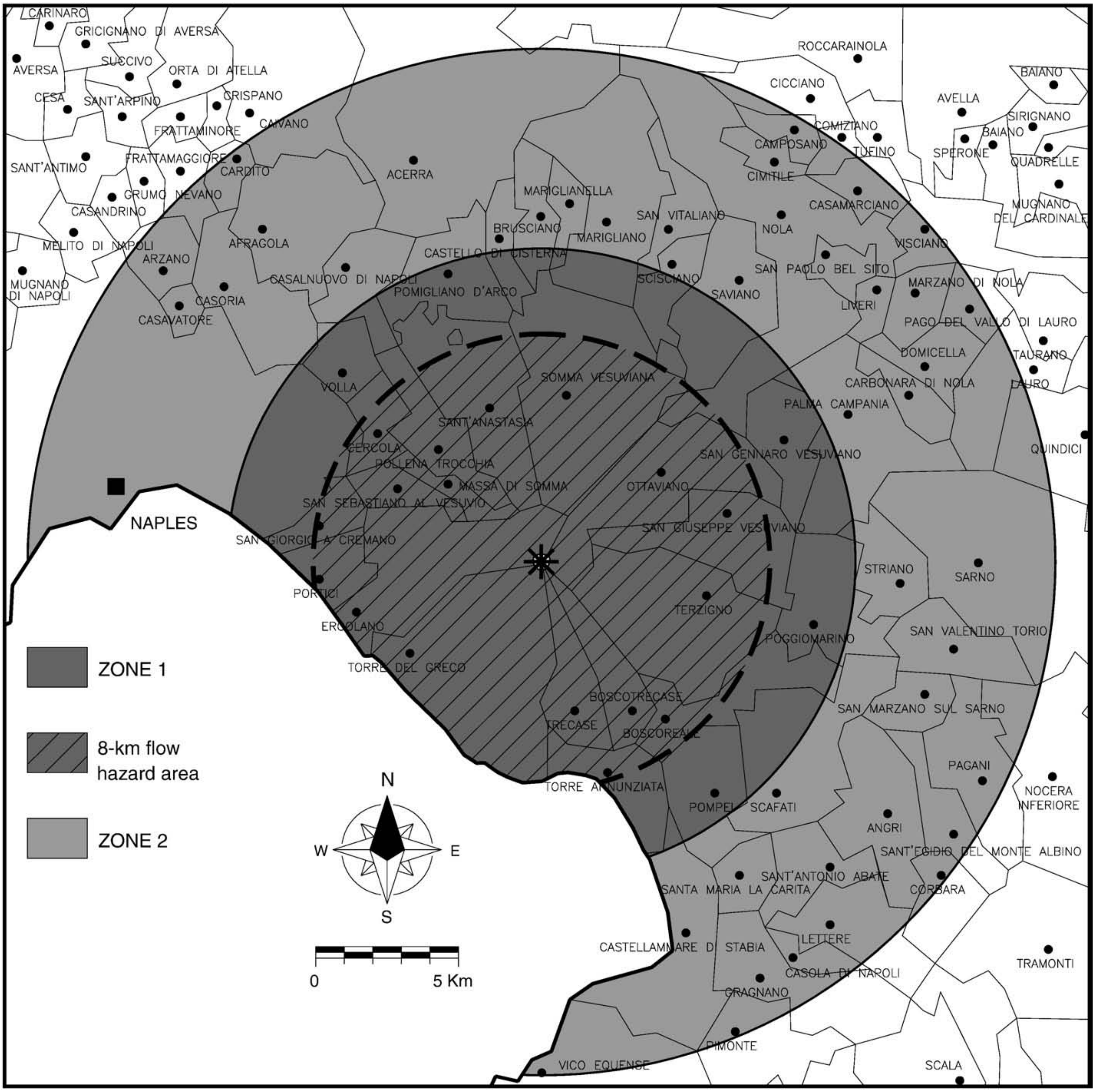


Fig. 5. Pyroclastic flow and base surge hazard zones map: *Zone 1*—Area to be affected by future flows (the 8-km area of the zone 1 is the area of greatest potential hazard for pyroclastic flows and base surge). *Zone 2*—Area of very low potential hazard for pyroclastic density currents, likely to be mostly affected by ash clouds associated with pyroclastic flows and base surge.

outcome of this is that a great number of critical buildings such as tenement-houses and a hospital, are placed only 100 m away from the current Red Zone, completely included in the 8-km area of greatest potential hazard for pyroclastic density currents defined in this work (Figs. 8, 9).

5.2.2. Tephra fall-hazard zone

This zone is extended beyond the range of the flow hazard area, but is still potentially affected by significant tephra fall from future eruptions. We have already seen that the majority of ash fall beds erupted at Somma-Vesuvius lie east of source vent (Fig. 10A), and these data suggest that most tephra from a future eruption will likewise be deposited east of the volcano. The wind direction prevailing during a future eruption may, however, be judged not only from past tephra fall dispersion, but also from modern wind records (Till Alison et al., 1993). The meteorological data collected in the weather stations of the Aereonautica Militare data center at Pratica di Mare (Rome) and Brindisi, in the periods 1986–2004 and 1976–2003, respectively, have been considered for winds at 20–40 km altitude (Fig. 10B). The data are quite similar for both the stations, and as the volcano lies roughly equidistant between the two stations they fairly well characterize the prevailing high level wind conditions in the atmosphere above the Somma-Vesuvius region. Wind data indicate that for Autumn and Winter seasons the prevailing direction is from the southwest

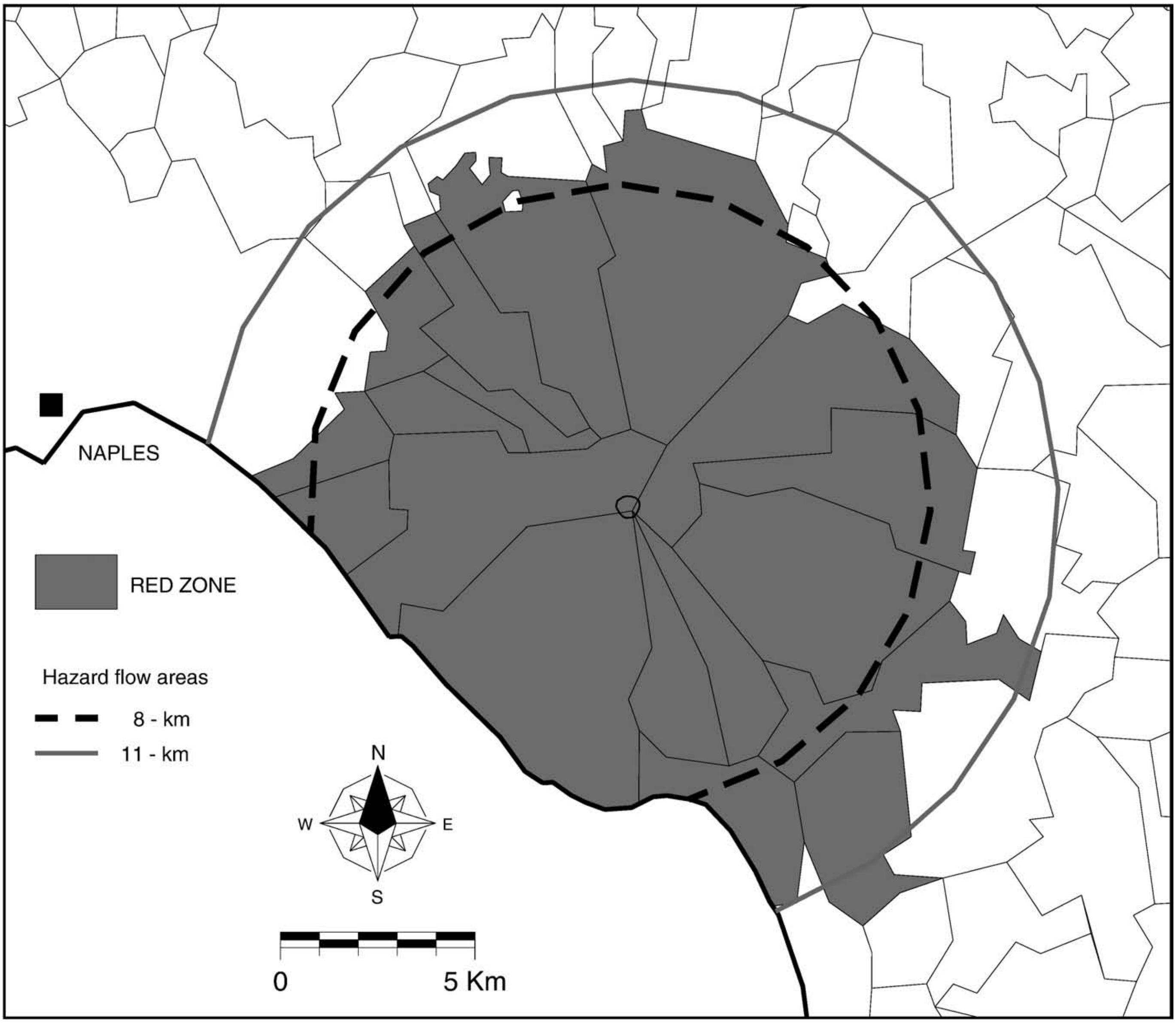


Fig. 6. Comparative analysis between the Red Zone of current plan and flowage hazard zones of Fig. 5. Note the shifting of outer limits of 8 and 11 km hazard zones respectively, with the outer limits of the current Red Zone.

(260°) and less commonly from the northwest (280°). In Summer the prevailing direction is from the east (90°), whereas in May and September winds appear marked by an evident transitional high altitude regime blowing toward both the west and the east directions (Cornell et al., 1983; Sigurdsson et al., 1985; Rolandi et al., 2007). The seasonal character of high level winds blowing above the Somma-Vesuvius region indicates that the tephra will be deposited by winds blowing not only from the west (Fig. 10B). In addition, there are other reasons for assuming that prevailing winds are not from the west at the time of a future eruption, such as seasonal periods of low wind speed, or different directions of tephra dispersion at different elevations of the eruptive column of a future eruption (Sarna-Wojcicki et al., 1981). One could quote the example of the 1906 Vesuvius eruption that was characterized by variable wind patterns, initially from the west and then from the east, producing tephra lobes oriented both toward Avellino (NE) and Naples (W–NW) (Mastrolorenzo et al., 1993). Significant damage resulted from the weight of tephra deposited to the east which caused structures to collapse at S. Giuseppe Vesuviano (216 people died and 112 were injured), Ottaviano and Somma Vesuviana. Significant damage resulted also from the weight of tephra deposited to the west, in Naples, where people died from the collapse of the roof of a local covered market located in the Monteoliveto area, near Piazza Carità (11 people died and 31 were injured). In addition, one ought not to underestimate that pyroclastic flows could be the source of an ash laden volcanic plume blowing across all the sectors of the volcano. One could quote the example of the AD 79 eruption: "*... shortly afterwards that cloud* (a share of the eruptive column) *came down on the land and covered the sea: it has already wrapped and buried Capri and it has made Capo Miseno scarce ...* (Pliny the younger, 2nd letter to Tacito)". We point out that Capo Miseno is to the west of Vesuvius, 30 km away from Naples.

Remarking on the potential zone to be affected by pyroclastic falls (The Yellow Zone), the emergency plan includes an area of 1100 km^2, mainly extending to the east (Fig. 4). Assessment of hazard from tephra fall around Somma-Vesuvius is largely based on the volumes of the past Plinian eruptions (Barberi et al., 1990; Lirer et al., 1973, 1997a,b, 2001), which are considered evidence for assuming that

Fig. 7. Detailed map of the northern Red Zone limits, at the Pomigliano d'Arco–S. Anastasia municipality boundaries. Note the anomaly of the small blue zone of the Pomigliano municipality included in the S. Anastasia municipality Red Zone. The 8-km limit trough the small area is shown as reference.

prevailing winds toward the east will be the actual winds at the time of the eruption. For the above-mentioned arguments, an alternative, more widespread and articulate Yellow Zone should be considered (Fig. 11), taking in account the possibility that at the time of the eruption winds will be blowing from the east, including a large part of the Naples area.

5.2.3. Flood hazard zone

Floods are commonly produced by heavy rains that generally accompany eruptions. For that reason a hazard zone might be threatened all around the Somma-Vesuvius volcano by floods from future eruption. Floods and debris-flow deposits related to historical eruptions (AD 472, AD 1631) are present in areas all around the volcano for long distances from the summit (Fig. 2), and are often recognized because they are not covered by primary flow deposits. These areas extend for great distances, of the same order as those for pyroclastic density currents, e.g. the Pietrarsa locality (S. Giorgio a Cremano) is 9 km from the summit of Vesuvius (Figs. 2, 3H). In May 1998 a long continuous rainfall period in the Apennine area east of Somma-Vesuvius highlighted the relationships between strong meteoric events and re-mobilisation of tephra lying on the flank of the Apennine limestone mountains. It must be observed that prolonged rainfall that occurred during the 1631 eruption was responsible for floods and debris flows in distal areas from Somma-Vesuvius, generating a very dangerous zone all around the Apennine area, as described in the chronicle of the eruption (Giuliani, 1632, pp. 144–145):.. *On Thursday 24 (December 1631)… rivers flowed from mountains of Visciano, Gaudo, Montevergine, Avella, Baiano.… Rivers also flowed from the Lauro mountains, inundating and destroying the plain of Palma and sediments thickened up to 16 spans, so that no species of trees is now seen among as much as the trees full of fruits which once covered the Plain.*

Fig. 8. Detailed map of the western Red Zone limits at the Naples municipality boundaries. Note the presence of critical buildings (Ospedale del Mare) included between the limit of current Red Zone and the 8-km flow hazard area.

In our opinion, the mudflow hazard zone, in which mudflows from future eruptions are possible, includes also the Naples hilly district (Camaldoli, Posillipo, Vomero, etc.) on the west side of Somma-Vesuvius. We recall that such events were triggered in the Naples area by past eruptions of Somma. The historical resort of Naples was destroyed from floods from the AD 472 eruption, running down the slopes of the hilly district. The mudflow deposits which covered the Greeko-Roman city are now seen around the museum underlying the church of S. Paolo Maggiore in Naples. Such events occurring from a future explosive eruption of Vesuvius have been defined as *secondary volcanic risk* (Rolandi et al., 2000).

Remarking on the Flood hazard zone of the Italian Civil Protection plan it considers the *blue zone* as the area affected by tephra fall with characteristics of the Yellow Zone, and by secondary volcanic hazards due to pyroclastic debris flow and floods. For the areas around the Somma-Vesuvius the flood hazard forecast of the Civil Defence has been amalgamated with the Red Zone, applying the criteria that near the volcano a specific flood zone is not shown because it does not extend beyond the flow hazard zone. We have observed, however, that past floods and debris flows were able to cover wide areas which extend beyond the shorter limits of the current Red Zone (we recall that the minimum distance of the Red Zone from the summit are 8 km), so the above criteria appear not to be appropriate considering the inadequacy of the current Red Zone. The hazard zone from future floods must be considered also to include the vulnerable areas towards the Appennines. The May 1998 debris-flow events in the

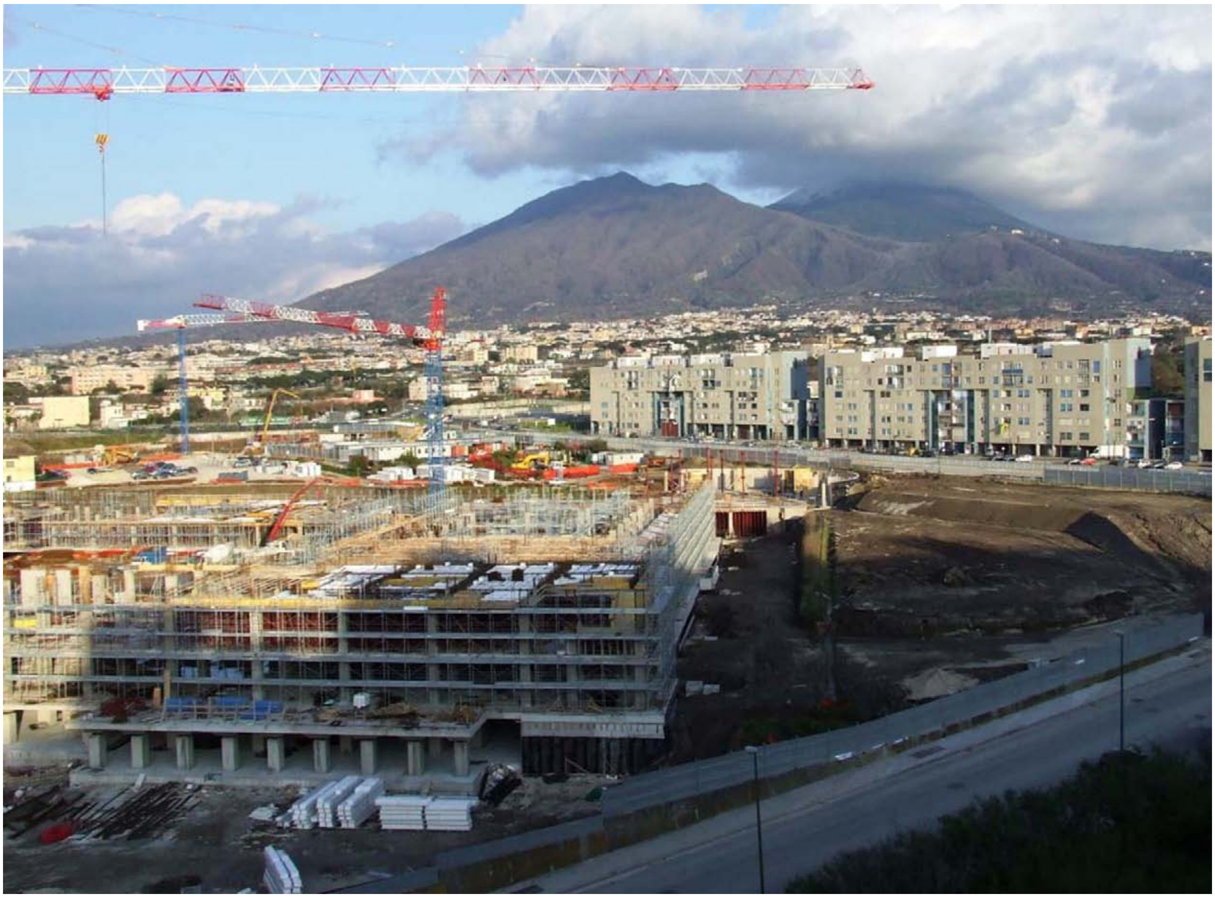


Fig. 9. The western critical area of Naples municipality. Note the high density built-up area (school, hospital, tenement-houses) at the base of Somma-Vesuvius. The area not enclosed in the current Red Zone, is enclosed in the 8-km flow hazard area.

Sarno area focussed the attention of the Civil Protection on the flood risk in the Apennines area, on making hazard assessments using GIS-based mapping techniques (Pareschi et al., 2002). It must be observed that risks from tephra debris flows were not considered in the original 1995 plan, notwithstanding the detailed descriptions in the 1631 eruption chronicles of these flowage events. The Blue Zone has been extended for about 150 km^2 through the so-called “Conca di Nola”, from Acerra to Nola (Fig. 4). It must be observed, however, that the 1631 chronicles refer to a wider region affected by such events, extended from Nola to Palma Campania and Sarno, eastward from Somma-Vesuvius, and through the Apennine valley, toward Avellino and Salerno, where important towns (Baiano, Lauro, Bracigliano, Siano, etc.) are exposed to a significant flood risk from a future eruption, indicating that the distal flood hazard scenario has been assumed only partially in the current plan.

6. Recommendations

Analysis of the Civil Protection plan has highlighted several problems that, in our opinion, cannot help to mitigate the effects of future eruptions. To be most effective, the Civil Protection plan must include the following recommendations:

1) The duration of the repose interval that started in 1944 cannot now be forecasted because as yet there is no known way to forecast when the next eruption will occur at Vesuvius. However, authorities might plan measures on the most severe case to mitigate the effects of a future eruption at Vesuvius, modifying the fundamental assumption that the next eruption will be preceded by weeks of precursory activity. Rather, the most effective scenario for the precursor events must be calibrated on a severe case, i.e. a future explosive eruption that strikes with little warning (less than a week). These extreme conditions must be taken in account as playing the role of good training for planning time-critical measures to mitigate the effects of a future eruption at Vesuvius.
2) The eruptive history at Somma-Vesuvius suggests that a future eruption could produce flow events of various sizes and volumes like those that have occurred in the past. On this account it is necessary to define a zone with a radius of 11 km from the vent, based on flow events that occurred from historical eruptions on Somma-Vesuvius. The 8-km radius has been considered as *the area of greatest potential hazard for pyroclastic density currents* of Zone 1, and every area around the volcano included in this zone should be considered at very high volcanic hazard and risk. When the Civil Protection Plan considered the current Red Zone to be potentially vulnerable to flowage events, it introduced a fundamental error, for the Red Zone coincides with municipality limits. Such a choice appears as an administrative (or politically motivated?) measure rather than as the result of careful volcanological survey. This boundary manifests confusion near the Zone's outer border and leads to a patently severe misunderstanding, both when the volcano is in repose and when it erupts. Misunderstanding thwarts careful evaluation for land development all around the dormant Somma-Vesuvius; miscalculation will lead inevitably to logistical problems during evacuation. It would be better to avoid confusion, taking up a different planning of the Red Zone in which the outer limit does not lend itself to a variety of interpretations. The flow hazard zone with the radius of 18 km must be considered for very infrequent events, and could actually play the role of an extended yellow Zone for ash laden volcanic plumes coming from

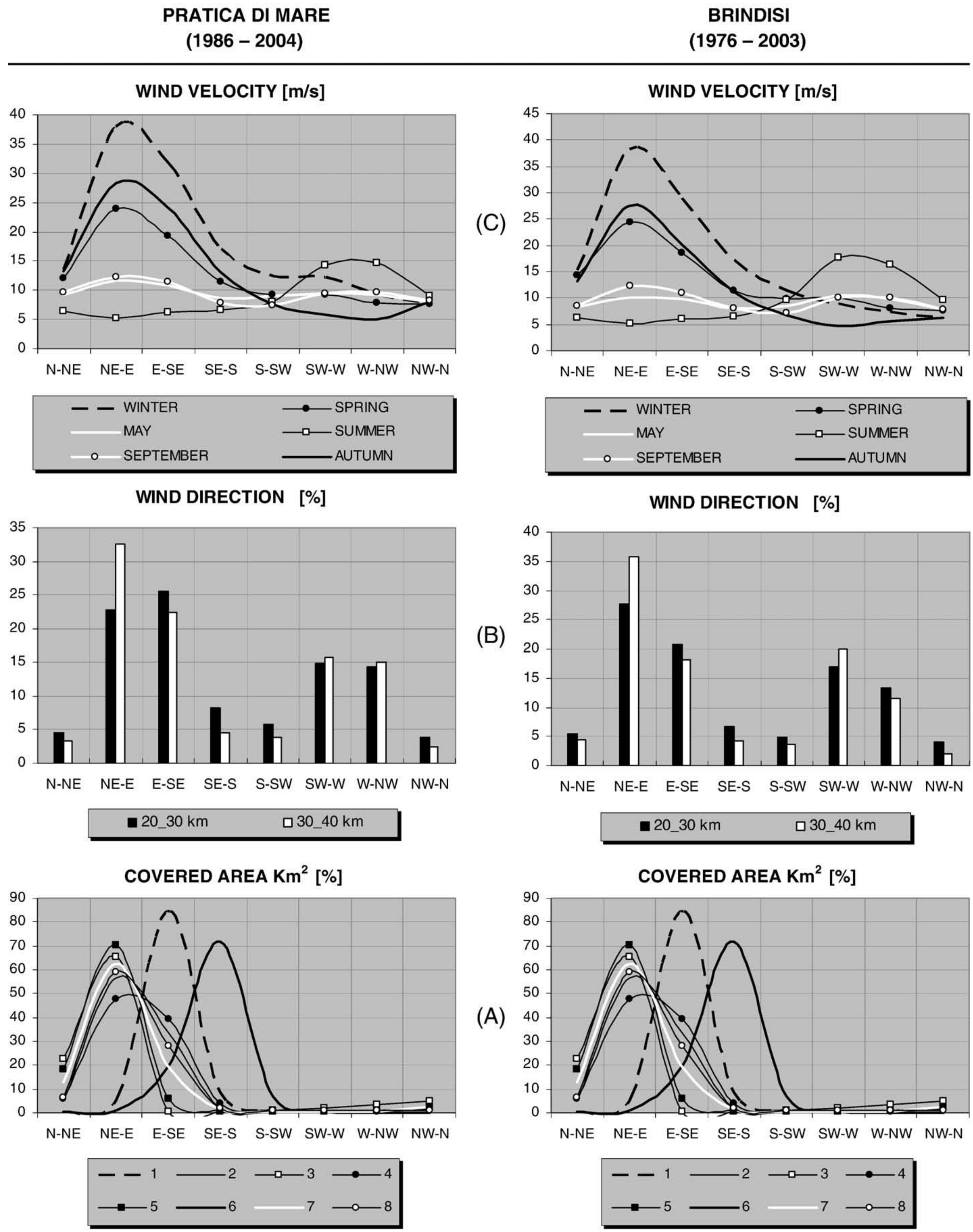
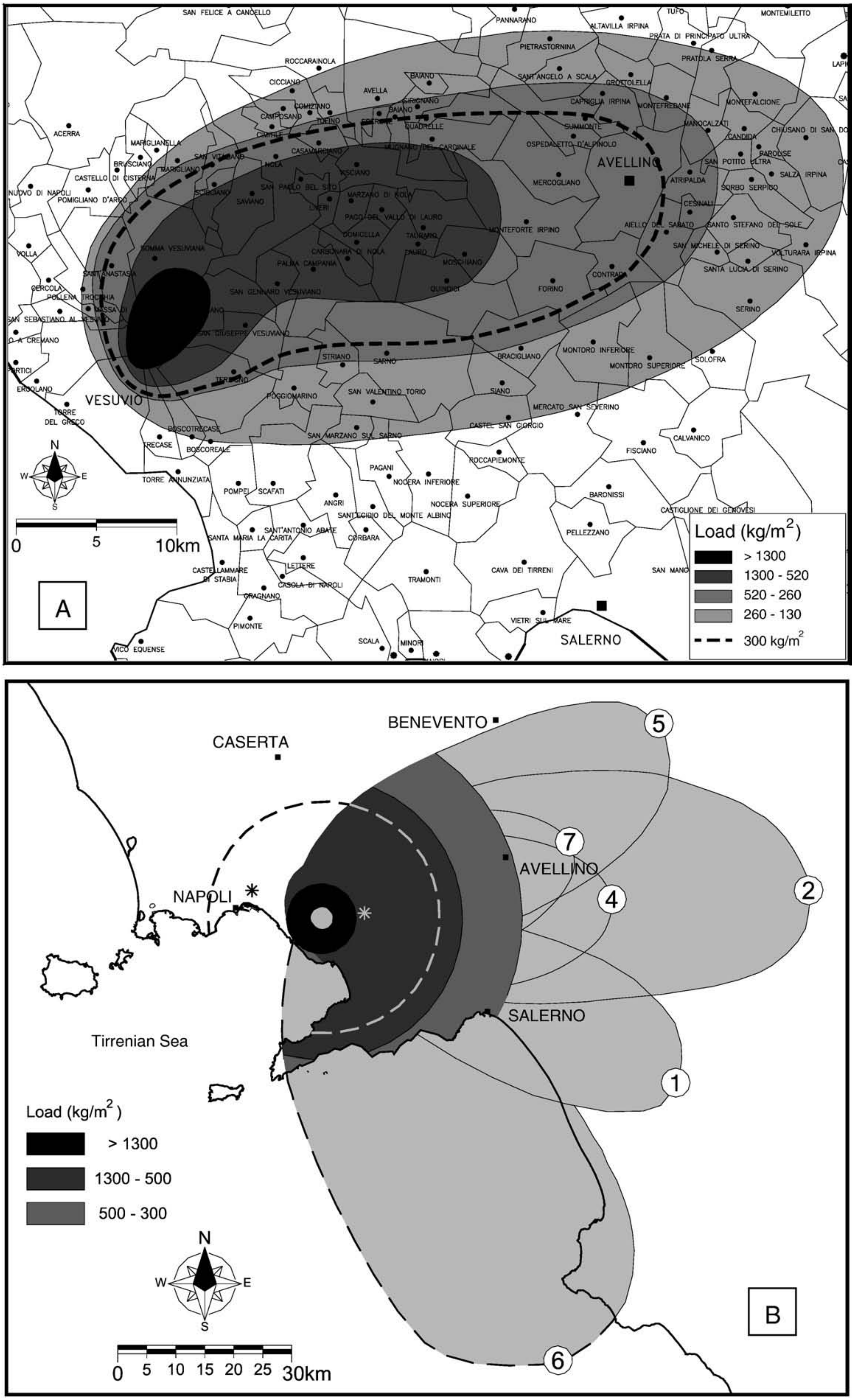


Fig. 10. (A) Maximum fall dispersion trough of the percentage of the sectors covered by 10 cm isopach (numbers as in Fig. 1 A, B) average high level wind directions in atmosphere above Somma-Vesuvius (data from Aereonautica militare data centers of Pratica di Mare-Rome, and Brindisi). Wind direction frequency diagrams showing average percentage of time that winds blow toward sectors centred on 8 principal directions. Note that the direction of dispersion of past tephra beds (from NE–E to SE–S) (diagram A) resemble the autumn–winter pattern showed by modern wind record (diagrams B), and (C) average seasonally wind speed.


A
Load (kg/m²)
> 1300
1300 - 520
520 - 260
260 - 130
300 kg/m²
0 5 10km
N
W E
S
VESUVIO
AVELLINO
SALERNO
SAN FELICE A CANCELLO
PANNARANO
TUFO
MONTEMILETTO
ALTAVILLA IRPINA
PRATA DI PRINCIPATO ULTRA
PIETRASTORNINA
PRATOLA SERRA
ROCCARAINOLA
BAIANO
SANT'ANGELO A SCALA
GROTTOLELLA
CICCIANO
AVELLA
SIRIGNANO
CAPRIGLIA IRPINA
MONTEFREDANE
MONTEFALCIONE
CAMPOSANO
COMIZIANO
TUFINO
MANOCALZATI
CANDIDA
CHIUSANO DI SAN DOMENICO
CIMITILE
QUADRELLE
SUMMONTE
ACERRA
MARIGLIANELLA
CASAMARCIANO
MUGNANO DEL CARDINALE
OSPEDALETTO D'ALPINOLO
SAN POTITO ULTRA
PAROLISE
BRUSCIANO
SAN VITALIANO
NOLA
VISCIANO
MARIGLIANO
SALZA IRPINA
CASTELLO DI CISTERNA
ATRIPALDA
SAN PAOLO BEL SITO
MERCOGLIANO
SORBO SERPICO
NUOVO DI NAPOLI
POMIGLIANO D'ARCO
SCISCIANO
SAVIANO
MARZANO DI NOLA
LIVERI
CESINALI
PAGO DEL VALLO DI LAURO
MONTEFORTE IRPINO
AIELLO DEL SABATO
SANTO STEFANO DEL SOLE
DOMICELLA
TAURANO
VOLLA
SOMMA VESUVIANA
CARBONARA DI NOLA
LAURO
SAN MICHELE DI SERINO
VOLTURARA IRPINA
MOSCHIANO
PALMA CAMPANIA
SANTA LUCIA DI SERINO
SANT'ANASTASIA
CONTRADA
QUINDICI
FORINO
CERCOLA
POLLENA TROCCHIA
SAN GENNARO VESUVIANO
SERINO
SAN SEBASTIANO AL VESUVIO
SAN GIUSEPPE VESUVIANO
MONTORO INFERIORE
SOLOFRA
STRIANO
SARNO
BRACIGLIANO
MONTORO SUPERIORE
TERZIGNO
ERCOLANO
POGGIOMARINO
SAN VALENTINO TORIO
SIANO
MERCATO SAN SEVERINO
TORRE DEL GRECO
BOSCOTRECASE
CASTEL SAN GIORGIO
SAN MARZANO SUL SARNO
CALVANICO
TRECASE
BOSCOREALE
ROCCAPIEMONTE
FISCIANO
PAGANI
TORRE ANNUNZIATA
NOCERA INFERIORE
BARONISSI
POMPEI
SCAFATI
ANGRI
NOCERA SUPERIORE
CASTIGLIONE DEI GENOVESI
SANT'EGIDIO DEL MONTE ALBINO
SANT'ANTONIO ABATE
PELLEZZANO
SANTA MARIA LA CARITA
CORBARA
LETTERE
CASTELLAMMARE DI STABIA
TRAMONTI
CAVA DEI TIRRENI
SAN MANGO
CASOLA DI NAPOLI
GRAGNANO
PIMONTE
VIETRI SUL MARE
SCALA
MINORI
VICO EQUENSE
B
BENEVENTO
CASERTA
NAPOLI
AVELLINO
SALERNO
Tirrenian Sea
1
2
4
5
6
7
Load (kg/m²)
> 1300
1300 - 500
500 - 300
N
W E
S
0 5 10 15 20 25 30km

pyroclastic flows, mainly toward the north and west where this zone is absent.

3) Once authorities have defined correctly the extent of the flow hazard zones, it will be imperative to examine all the portions of flow hazard areas not considered in the current Red Zone. The most important is represented by areas placed in the very eastern sector of the Naples municipality, as the area is included in the 8-km flow hazard zone. For that reason, in our opinion, the east Naples area is at particularly high volcanic risk. In this area many tenement-houses have been constructed in the last 20 years, including the new hospital ("Ospedale del Mare"). In this particular case authorities must take into consideration a specific risk level for planning the logistics of evacuation: e.g. will the evacuation of the hospital begin in the initial alarm phase, rather than in the full alarm phase?, see Table 2). The modest hospital of Sarno was evacuated in two days during the debris-flow landslide of 1998. For the much larger "Ospedale del Mare" at least five days need to be assumed necessary for the complete evacuation. In confirmation of this, the above recommendation, or others of a similar level, has to be included in written form in the plan. This is vitally important.
4) The assumption that prevailing winds from the west will be the actual winds at the time of a future eruption is incorrect. Assessment of hazard from tephra fall around Somma-Vesuvius based on the volume of the past Plinian eruptions deposited east of source vent, and on wind directions prevailing during future eruptions define the statistically likelihood that tephra will be carried by winds at the time of the eruption. However it is important also to remember that the actual transport and speed strictly depend on the wind pattern at the time of the eruption, and during the eruption. For the definition of the tephra fall-hazard zone, in our opinion, the Yellow Zone must be extended both to the east, as it currently is, and to the west, so as to include a large part of the Naples municipality (Fig. 11).
5) The emergency plan included the flood hazard zone in the Red Zone on the slopes of Somma-Vesuvius. In our opinion, this assumption needs to be modified so as to introduce a detailed flood scenario that is marked on the stream channel drainages extending on the sides of the volcano for long distances (i.e. Pollena valley, Cavallo valley, etc.). These affected areas could be more extensive than some outer limits of the current Red Zone. The so-called Blue flood hazard zone near the Apennine mountains (*secondary volcanic risk*) needs to be extended. It must include the Palma Campania plain (the area enclosed between the Sarno and Nola municipalities) and the Apenninic areas toward Avellino (NE), as well as Salerno (E–SE), where several towns are located near Apenninic river beds, and where there are good reasons for believing that a high flood risk occurs in conjunction with a future eruption of Somma-Vesuvius.

7. Conclusions

Having considered the main volcanological aspects related to the emergency plan for a future eruption of Vesuvius, we assert that potential problems arise from basing hazard evaluations on a 1631 eruption scenario. First, the assumption that the next eruption of Vesuvius will be subplinian, and that authorities will be able to forecast it weeks ahead of time, needs to be modified. Second, the fall distribution area (the yellow Zone) and the flowage hazard area (the Red Zone), as included in the current emergency plan, are drawn as safety devices developed from the AD 1631 eruption scenario. We have shown, furthermore, that the choice of the emergency plan's hazard zones must be modified by increasing the safety limits. In short, we firmly believe that the future hazard evaluations based on an AD 1631 eruption represent an unnecessary reference scenario. Third, to consider the flood hazard problem, the 1631 flood scenario, as described in the historical chronicles, appears adequate both for the proximal and distal areas; but this scenario, unfortunately, has been assumed only partially in the current plan. In sum, the problems of the volcanic hazard and risk scenario as depicted in the present work, and of the education to risk both for the administrators and population that live in the volcanic area (Solana et al., 2008), are not yet completely solved. It is discouraging to note that in the Naples municipality, shortly to the west of the Somma-Vesuvius, authorities have not carried out a policy of reduction of risk to life and property, which requires that the affected areas be avoided. We get proof to the contrary as they have planned the area to allow the significant increase of the volcanic risk by installing tenement-houses and critical buildings (such as the Ospedale del Mare). In the light of the above considerations we call for substantial reconsideration of the current emergency plan, because upon its functionality will depend the life of the people living all around Vesuvius.

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Fig. 11. Fall-hazard model based on the AD 472 and 1906 eruptions as possible analogue for a future explosive eruption: (A) AD 472 isopach map (Rolandi et al., 2004) indicating the area in which mass accumulations of tephra can lead to roof collapse; (B) Probable autumn–winter fall-hazard area toward east drafted by extending the hazard area of panel (A) over the whole area covered by tephra fall deposits in the past (see also Fig. 1). The area inside the circle corresponds to the 1906 impaired area (stars indicate the locality where the eruption caused the victims for the roof collapse). It is considered here as a minimum impaired area for a summer-westerly wind direction, or for unusual tephra dispersal of the future eruption, both the occurrence leading to roof collapse also in the Naples urban area.

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