Urban Habitat Constructions Around Vesuvius: Environmental Risk and Engineering Challenges

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ABSTRACT

Vesuvius is an active volcano in the Bay of Naples and within 8 km radius of its crater live today more than half a million people. In the past Vesuvius devastated the surrounding territory and a medium- or large-scale eruption will be catastrophic, unless a sustainable habitat is constructed for Vesuvians. The new environment should include community participation, project a sense of belonging and pride, be self-adapting and efficient in providing and managing services, minimize geographical and resource footprints, and above all be safe from future eruptions and manageable. The design and construction of this urban habitat present a grand challenge for city planners, economists, engineers, and other professionals in terms of utilizing materials, securing commerce and energy supplies, disposing of waste products, and protecting the city and its infrastructure during emergencies. To accomplish this goal we must employ proper risk assessment tools and overcome the complacency of Vesuvians and their representatives in local and national governments.

1 INTRODUCTION

1.1 *Neapolitan volcanoes*

Within 50 km radius of Naples in Southern Italy live today about 3 million people and they are exposed to the high risk of explosive eruptions of Vesuvius and Phlegraean Fields. When these volcanoes erupt they can produce enormous environmental impacts and completely obliterate the nearby human habitats. Naples is situated in the middle of these volcanic complexes and constructed on the deposits of their eruptions. The Phlegraean Fields (Campi Flegrei) on the west of Naples erupted the Campanian Ignimbrite some 40,000 years ago and the Neapolitan Yellow Tuff some 15,000 years ago (Orsi et al. 1996). More recently, it erupted in 1538 and during 1982–1984 the central Pozzuoli area experienced considerable ground uplift (1–2 m) which subsequently deflated with the seismicity remaining at very low levels (De Natale et al. 1991, Guidarelli et al. 2006). About half a million people live today in the immediate vicinity of this volcano whose very large eruptions are not common (tens of thousands of years), but devastating for the entire Campanian Plain and beyond.

The eruptions of Vesuvius to the east of Naples are of lower energies than those of Phlegraean Fields, but more frequent and today would be comparably devastating for the entire Neapolitan area because of the high population densities which border this volcano. Vesuvius was formed some 25,000 years ago inside the older stratovolcano Somma with an age of about 400,000 years (Brocchini et al. 2001). This volcano produced at least 8 large-scale plinian eruptions and many smaller scale subplinian explosive–effusive eruptions between each plinian cycle (Arnò et al. 1987). Each plinian eruption discharged between 2 and 6 km^3 of material and its deposits consist of ash and pumice falls from eruption clouds, pyroclastic surges and flows produced from partial or total collapses of volcanic columns, debris flows or *nuèe ardentes* produced from the rupture of volcanic edifice, and mud flows or *lahars* caused by the fall of wet ash from the condensation of water in the plume. The last plinian eruption in 79 A.D. buried the surrounding towns of Pompeii and Herculaneum (Sigurdsson et al. 1985) and its effects were felt as far as Miseno (Radice 1963), some 60 km away on the western age of Bay of Naples. The last subplinian eruption occurred in 1631 when some 4000–10,000 people died from *nuèe ardentes* and *lahars*, and since this time the volcano produced many strombolian and effusive eruptions as its volcanic conduit(s) was attempting to close. The last eruption occurred in 1944 when the Allied Military Command evacuated some 15,000 people from the nearby town of San Sebastiano al Vesuvio as it was being destroyed by the invading lava flows (Imbò 1949, Pesce & Rolandi 1994).

1.2 *Habitats around Vesuvius*

The Campanian Plain is built from the eruption deposits of Vesuvius and Phlegraean Fields and its inhabitants live today in the dwellings constructed on these deposits. The Vesuvius area (Fig. 1) was first populated in the pre-historic time; in the eight century B.C. was colonized by the Greeks and later by Romans, Byzantines, Normans, Angevins, Aragoneses, and Spaniards, until it was integrated into the modern Italian state in 1860s. Today, about 550,000 people live in 18 towns surrounding the volcano and within 8 km of its crater. The most significant population increase took place after World War II when some towns like Portici doubled and tripled in the number of people in order to decrease the demographic population increase of Naples. Torre del Greco is the largest town in the area with some 90,000 people.

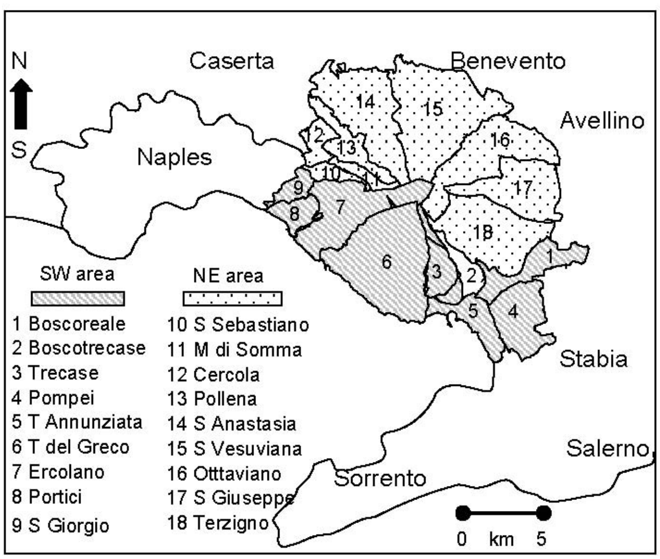


Figure 1. The Vesuvius area includes 18 municipalities which are situated within 10 km radius of the crater.

About 40% of active population is in commerce and about 30% in construction and manufacturing. The rest of the people work in public service, education, agriculture, and other sectors. Compared to a century ago, this population has in effect been transformed from an agriculturally-based to commerce-, construction-, manufacturing, and service-based society where too many people are involved in illegitimate activities (Di Donna 2006). The Vesuvius area population is also poorly educated, which prevents the people from judging correct from incorrect risk management strategies for the territory (Dobran 2006a, Dobran & Sorrentino 1998). Our survey also indicates that over 80% of the people are uninformed of the risk posed by the volcano and that they have very little confidence in risk management authorities. In the event of danger, they are highly skeptical about evacuating on time and prefer to remain on the territory where a better future should be created for them.

1.3 *Choices for the future*

After the eruption of 1944 the ever present smoke from Vesuvius has disappeared and its slopes began to be veiled in asphalt and concrete. Massive building speculation and absurd urbanization without regard for the environment has produced a habitat with degrading social and cultural services, and brought man and nature one step closer onto the collision course. This collision must be avoided. We can: (1) do nothing and wait until the first signs of unrest of the volcano and then try to evacuate the people as promoted through an unreliable evacuation plan drafted and promoted through the government by the geologists, (2) depopulate the territory forcefully in order to reduce the human footprint and thus alleviate evacuation of hundreds of thousands of people on short notice (1–2 days), or (3) begin constructing a sustainable urban habitat around Vesuvius that can confront future eruptions in security without crippling social services and economic structure.

An evacuation plan depends on the reliable prediction of eruption and existence of effective evacuation infrastructures. The prediction of an eruption is scientifically not possible more than one or two days in advance in the situation of large eruptions (Swanson et al. 1983), or altogether impossible for very small ones (NYT 1997). Vesuvius evacuation plan (Protezione Civile 1995) requires three weeks to evacuate half a million people by assuming that frequent earthquakes and ground deformation will not cripple transportation services (trains, boats, trucks) during this time and that the people will not panic. It also assumes that the evacuees can be relocated all over Italy and that the neighboring populations of several million people will remain passive during the massive exodus. Apart from detrimental social and cultural implications, such a strategy is technically unreliable and is being supported by those who are either technically blind or need a protection from the consequences of a catastrophe.

The second choice of forcefully depopulating the Vesuvius area has been practiced for some time, either intentionally or not, as witnessed by the deteriorating social and cultural services (Di Donna 2006). One cannot now simply tell the Vesuvians to leave the area after telling them for decades to settle it, without producing elsewhere the necessary socioeconomic incentives. But one can apparently keep the population from reaching its full potential by ensuring that it is badly governed.

In this paper we will concentrate on the third choice that aims at constructing a sustainable habitat for people around Vesuvius. This strategy promotes a security culture instead of an emergency culture, for its central objective is to produce security and prosperity conscious citizens where the volcano is not viewed as a menace but as an asset that is capable of attracting great resources for the reconstruction of the territory. Toward this end we discuss in Section 2 the necessary concepts of risk assessment and how this is employed in an urban setting that is subjected to different types of anthropogenic and environmental hazards. We will quantify the current knowledge of the substructure of Vesuvius, seismicity of the volcano-tectonic area, and different types of hazards produced from different types of eruptions. Global Volcanic Simulator is a tool for the analysis of many volcanic hazards, and together with the seismic analysis tools and vulnerability of structures and other data can be employed to carry out the most reliable quantitative risk assessment for the territory. This information and additional socioeconomic and urban planning elements can be utilized to design a sustainable habitat for the people around the volcano, provided that the urban planners and engineers overcome some of their difficult challenges (Section 3). Section 4 summarizes a feasibility study that aims at producing environmental, economic, sociological, educational, and risk management guidelines pertaining to the design of Vesuvian habitat. The scrutiny of these guidelines should eventually produce a convergence of different interests and enough resources leading to the implementation of effective decisions. We should in fact seriously rethink urbanization in the entire Bay of Naples if we are to prevent future Pompeiis.

2 ENVIRONMENTAL RISK

2.1 *Risk analysis procedure*

When asking ‘what is risk?’ one can ask three questions: What can happen?, How likely is that to happen?, If it does happen, what are the consequences? (Kaplan 1997). Quantitatively, risk is a ‘measure’ and as such involves all possible scenarios S_i, likelihood of each scenario L_i, and consequences of the *i*th scenario X_i, i.e.

$$R = \left(S_i, L_i, X_i\right)_c \tag{1}$$

Here ‘c’ stands for complete to emphasize that we need to know all possible (or at least the most important) scenarios. One can think of R as a trajectory in the $3n$ dimensional phase space spanned by the triplets $S_i, L_i, X_i : i = 1, ..., n$.

Possible scenarios for the Vesuvius area include those that are not necessarily associated with the volcano (earthquakes, landslides, releases of hazardous chemicals, terrorist activities) and those that are. The former scenarios can be produced from the anthropogenic sources and the tectonic motions of African and Euroasian plates that under the Mediterranean Sea slide relative to each other, causing, among other things, the opening of the Tyrrhenian Sea and the volcanic belt surrounding it (Panza et al. 2007). The latter group of scenarios incorporates some members of the former group and also includes: Tephra and ballistic blocks falls from eruption columns; pyroclastic flows, surges, lavas, and lahars propagating along the slopes of the volcano; dome collapses; ruptures of volcanic edifices; emissions of deadly gases; and tsunamis produced from landslides and pyroclastic flows propagating into the Tyrrhenian Sea.

A scenario has an associated ‘as planned’ or reference scenario, S_o, but this may not be reachable with 100% confidence because an initiating event (IE) changes its course in phase space (Fig. 2a). This produces the risk scenario S_i which may have one or more end states (ES), depending on the system complexity. We have in fact a 'scenario tree' and each initiating event produces in general a different tree. Each scenario tree can produce several end states, and there may be situations when some of these states are common to two or more paths coming from the same tree or different trees. But instead of looking at the trees being driven by the events we can identify the end state of interest and draw the incoming tree whose branch ends converge on different initiating events (Fig. 2b). One can also identify one or more middle end states and establish the associated initiation events and other states. There are other interesting methods for analyzing scenarios that are not discussed here. The scenario determination methodology can take different routes and may thus reach quite different conclusions.

The likelihood of scenario L_i in Equation (1) may take the form of a frequency, probability, or probability of frequency. Frequency f_i applies when the law of large numbers applies; typically when a repetitive situation exists. Probability P_i is a 'one shot' situation and probability of frequency $P_i(f_i)$ applies when a repetitive situation exists, but we are uncertain about what that frequency is.

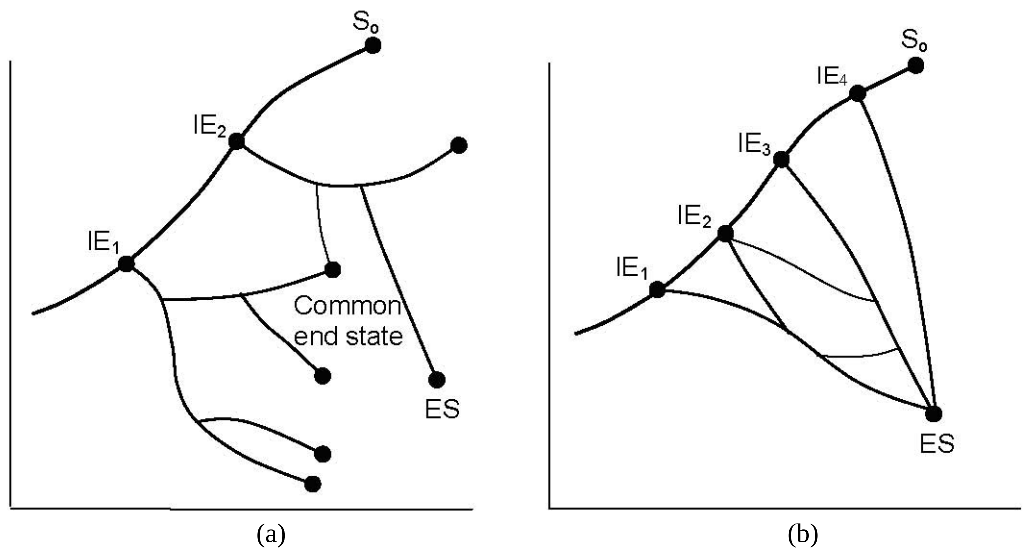


Figure 2. (a) Scenario 'event trees' issuing from different initiation events (IE) have one or more end states (ES). (b) Incoming scenario tree (fault tree) starts from an end state and produces different initiation events. S_o is 'as planned' or reference scenario.

The consequences are damages to people, property, environment, wild life, etc., and in general can be expressed by probability curves $P_i(X_i)$. These curves express uncertainty, and since we always have uncertainty we need to agree that the probability curves represent the truth which is vital to the decision process.

The risk analysis procedure described above should utilize: Our knowledge of the substructure of the volcanic system; properties of subsurface materials in their liquid, solid, and gaseous states; properties of the atmosphere above the volcano into which the volcanic products are discharged; topography of the volcanic edifice; our physical modeling capabilities of different types of volcanic processes; and the vulnerability of our cultural patrimony and life forms residing on the slopes of the volcano. As further elaborated below, all of these elements can then be combined into a risk assessment methodology that can be subsequently used for making decisions and taking actions.

2.2 *Seismicity and substructure of Vesuvius*

The Vesuvius area has been inhabited for several millennia during which time several large and well-documented eruptions occurred, but little is known about the earthquakes associated with these eruptions. The historical sources provide little information about the seismicity that preceded the eruptions of 79 and 1631 (Marturano 2006). In 62 A.D. a large earthquake (estimated to be of magnitude $M = 5$) caused extensive damage to the towns surrounding the volcano, but there is no clear indication that it is connected with the eruption 17 years later. Other earthquakes of lower energies also struck the area preceding the famous eruption (Fig. 3), but following this eruption and until the subplinian eruption of 472 the historical sources record no earthquakes with the epicenters under the volcano. Although some earthquake damage in Nuceria (modern Nocera) is related to the eruption of 472 (De' Spagnolis 2000), no records of earthquakes appear to exist for the eruptions that occurred in 685, 787, 1036, and 1139 (Figliuolo & Marturano 1997).

According to Braccini (1632), several months of seismic activity preceded the last subplinian eruption of 16 December 1631 and on the day before the volcano produced an earthquake of magnitude $M = 4$ that was felt in Naples. Smaller magnitude earthquakes continued during the day and into the night of 16 December until the eruption around 7 a.m. (Fig. 4). From 1631 to 1944 the volcano attempted to close its conduits and during this time numerous small-scale strombolian and effusive eruptions occurred (Nazzaro 1997). These eruptions produced earthquakes that remained below $M = 4$.

Since 1944 the Vesuvius area has been experiencing several hundred earthquakes per year with low to moderate energies, and since 1971 Osservatorio Vesuviano in Naples has maintained a local seismic network to monitor the Neapolitan volcanoes (Castellano et al. 2002). These earthquakes are concentrated within 1 km radius of crater axis and at depths less than 6 km below the sea level (Bianco et al. 1999, De Natale et al. 2004a, Del Pezzo et al. 2004). The recent seismicity at Vesuvius (Fig. 5) consists of the background seismicity with some tens of earthquakes per month and energies $M < 3$, periods of increased seismic events of low energies, and a number of earthquakes with high energies ($M \geq 3$) that are not preceded with large number of events. The largest earthquake ($M = 3.6$) occurred on 9 October 1999 at about 3 km beneath the central cone and was felt within about 25 km of the volcano. It caused fear and anxiety among the people. This behavior of the volcano may be associated with magma movements into the superficial regions of the system or volatile exsolution from magma differentiation, but there is no clear indication that Vesuvius will erupt anytime soon (De Natale et al. 2004a).

The substructure of Vesuvius can also be inferred from the deposits around the volcano and seismic tomography studies. The volcanic deposits around Vesuvius contain limestones, various thermometamorphosed marble and skarn lithic ejecta, and suggest that the location of magma chamber and/or magma fragmentation levels lies within the Mesozoic carbonate basement, somewhere between 3 and 5 km below the surface of the volcano (Barberi et al. 1981, 1989). The subplinian deposits do not contain carbonate lithic ejecta, suggesting that magma reservoirs and/or magma fragmentation levels were located above this basement whose top lies at a depth of about 3 km (Bruno et al. 1998). Geophysical studies and analysis of data obtained from a seismic tomography experiment do not, however, validate the volcanological data and suggest that magma should exist at depths that are greater than 5 km below the sea level (Zollo et al. 1996, 1998: Greater than 10 km; Auger et al. 2001, Civetta et al. 2004: Greater than 8 km; De Natale et al. 1998, Scarpa et al. 2002: Greater than 5 km; De Natale et al. 2004b: Greater than 6 km; Natale et al. 2005, Guidarelli et al. 2006: Greater than about 10 km; Nunziata et al. 2006: About 8–10 and 20 km). Seismic tomography data suggest a very low shear velocity (~ 1 km/s) layer at about 9 km depth (Auger et al. 2001) and, based on the geophysical modeling, Nunziata et al. (2006) estimate that its thickness does not exceed 0.4 km. The volume of this sill containing partial melt is comparable to the cone of Vesuvius and it resides above a much larger hot mass that forms the magmatic reservoir for Campanian volcanoes. Based on petrological studies, Lima et al. (2003) argue for small magma chambers at depths greater than 3.5 km and for the possibility of a larger chamber below 12 km.

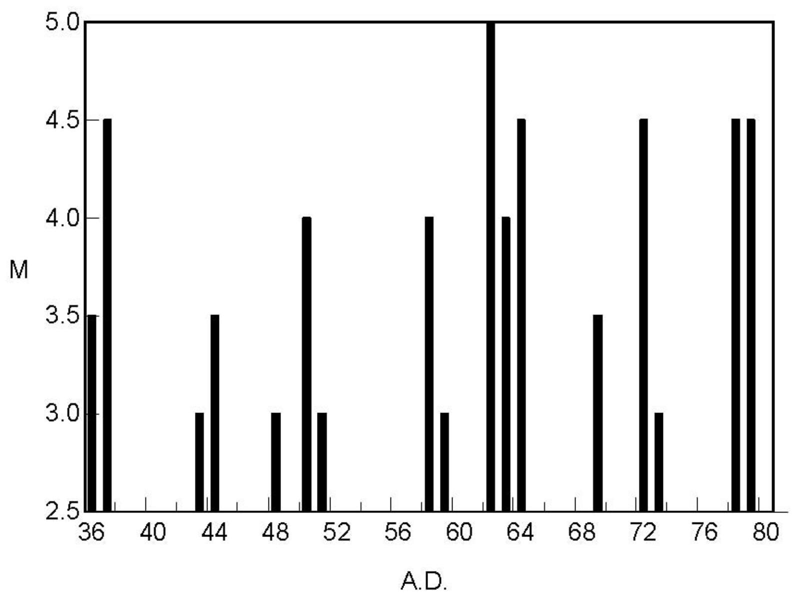


Figure 3. Estimated magnitudes of earthquakes preceding the eruption of 79 A.D. Earthquakes from historical sources include those that are dated (37, 62, 64, 79 A.D.) and those that are not dated. Earthquakes from archaeological sources (62, 72, 78, 79 A.D.) are responsible for damages. Adapted from Marturano (2006).

The location of magma and the amount, concentration, and properties of molten material below Vesuvius are thus uncertain, both because of the uncertainty of petrologic data and the inverse problems of seismology which reflect the combined effects of the source and medium, neither of which is known exactly. If magma is close to the crystallization state in the superficial regions and molten state in deeper regions of the volcano, the situation can rapidly become unstable if the permeability of the region is sufficiently large. When this occurs, magma can rise to the surface in several days (Dobran 2001).

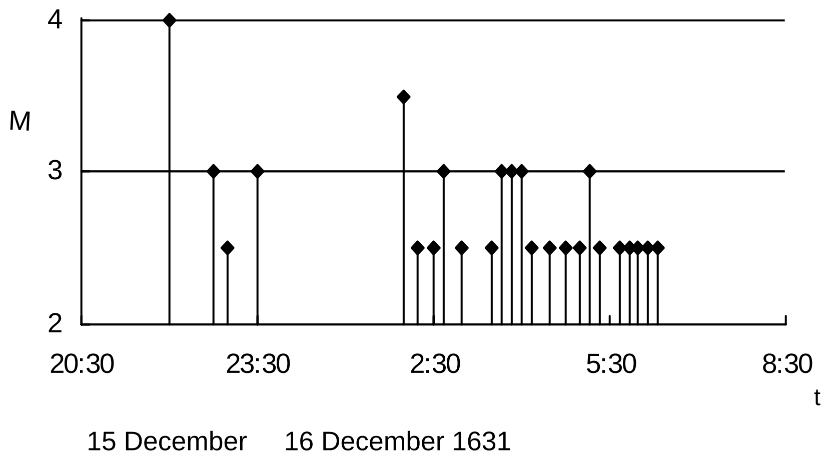


Figure 4. Estimated magnitudes of earthquakes preceding the eruption of 1631. Adapted from Marturano (2006).

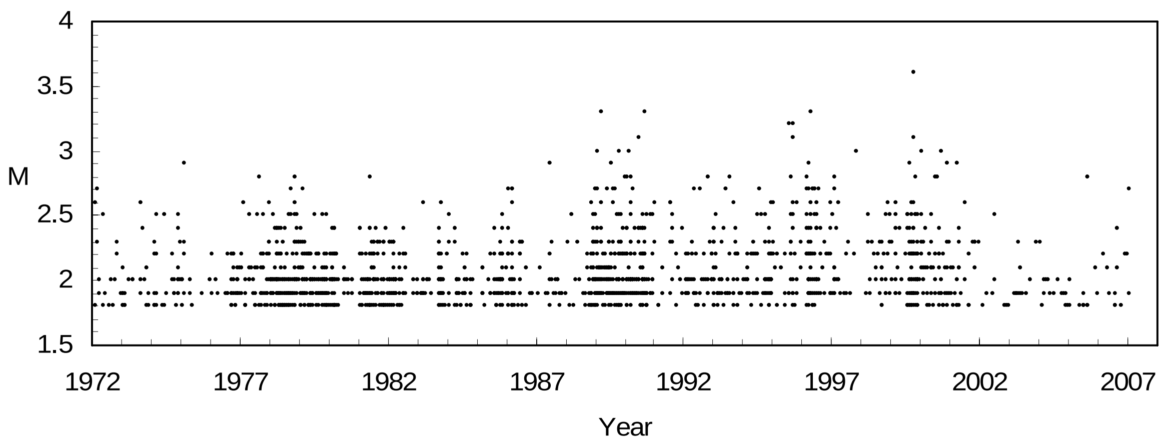


Figure 5. Distribution of recent earthquakes at Vesuvius with $M \geq 1.8$. Adapted from De Natale et al. (2004a) using earthquake catalog data of Osservatorio Vesuviano.

2.3 *Tephra fall, pyroclastic flows, and lahars*

During the past 25,000 years Vesuvius produced at least 8 large-scale pumice-fall and pyroclastic-flow eruptions and many medium- and small-scale eruptions between the plinian cycles (Arnò et al. 1987, Nazzaro 1997). Each plinian eruption discharged between 2 and 6 km^3 of material and each subplinian eruption an order of magnitude or so less material. The deposits of these eruptions consist of ash and pumice falls from eruption clouds, pyroclastic surges and flows produced from partial or total collapses of volcanic columns, debris flows or *nuèe ardentes* produced from the rupture of volcanic edifices, and mud flows or *lahars* caused by the fall of wet ash and rain from eruption columns.

For the purpose of constructing survivable human habitats around the volcano it is important to know the characteristics of eruption deposits at different locations from the crater. But the farther we go back in time the more difficult it is to find these deposits, since they have been covered by the products of subsequent eruptions and more recently by a network of dense human dwellings.

Table 1 summarizes some of the available data pertaining to the fall of tephra and propagation of pyroclastic flows and surges of several well-known plinian and subplinian eruptions. It should be kept in mind that this information provides only a rough guidance as to the potentiality of the hazards involved, because the deposits thicknesses depend on the eruption parameters, prevailing stratospheric winds during the eruptions, directions along which partial or total column collapses occurred, topography surrounding the volcano, and other parameters.

Table 1. Thicknesses of deposits and their locations around Vesuvius pertaining to tephra fall and pyroclastic flows for some plinian and subplinian eruptions. Estimated column heights and quantities of material erupted are indicated for some eruptions. Data are from Delibrias et al. (1979), Sigurdsson et al. (1985), Carey & Sigurdsson (1987), Rolandi et al. (1993a, b, c, 1998, 2004) and Rossi et al. (1993). Thicknesses of deposits are unique to the locations indicated.

Eruption	Fall deposits			Pyroclastic surges and flows		
	Thickness (m)	Distance (km)	Direction	Thickness (m)	Distance (km)	Direction
Basal 17,000 y.B.P. plinian	2 0.2	4.5 22	N NE	3.5	4	N
Greenish 15,000 y.B.P. plinian	1 0.4	4.5 9	N N	14 2	4.5 9	N N
Lagno Amendolare 11,000 y.B.P. plinian	2 1	4 20	NW E-NE	absent		
Ottaviano 8000 y.B.P. Plinian, 22 km, 3 km^3	4 3 1.5 0.5	5 10 20 30	N-NE N-NE N-NE N-NE	10 3.5 0.5 0.1	4.5 7 3.5 20	N NE NE NE
Avellino 3750 y.B.P. plinian 36 km, 4 km^3	0.8 1 0.6 0.1 1	6 15 30 40 3.5	E-NE E-NE E-NE E-NE NE	6 2 1 0.5 0.2	8 12 15 6 20	NW NW NW NE NW
Pompeii 79 A.D. plinian, 30 km, 3 km^3	14 4 2 1	5 8 20 40	W S-SE S-SE S-SE	15 10 2 3	5 8 8 10	W W-SW N-NE SE
Pollena 472 A.D. subplinian 20 km, ~ 1 km^3	1.3 1.2 0.9 0.3 0.7	5 8 20 30 10	NE NE NE NE NE	10-14 2 0.5	5 8 10	NW NW N-NE
1631 A.D. subplinian 20 km ~ 1 km^3	0.7 0.5 0.3 0.2 0.1	8 10 15 20 25	E-NE E-NE E-NE E-NE E-NE	0.3 0.2 0.1 4	5 10 15 7	E-NE E-NE E-NE S

The Mercato–Ottaviano eruption occurred in the early pre-history some 8000 years ago and its products spread at least 70 km from the volcano. It is estimated that the eruption discharged about 3 km^3 of pyroclastic material in about 20 hours, its column height rose to about 22 km, and its variable eruptive activity produced tephra (ash and pumice) falls and pyroclastic surges and flows that swept toward the N–NE of the volcano or in the direction of Ottaviano.

The Avellino eruption occurred in the Bronze Age, around 1750 B.C. Based on the eruption deposits it is estimated that the first hours of the cataclysm produced an eruptive cloud almost 40 km high. The dense ash and pumice fall buried dwellings and villages over a vast area toward N–NE, in the direction of Avellino. The ash and pumice fall was felt in the mountains of Irpinia and the subsequent pyroclastic flows and surges and *lahars* deposited thick layers of debris over an area of more than 400 km^2. These flows traveled more than 20 km from the volcano, and in Casoria, at the north of Naples, produced 1-m-thick deposits. During 20 hours of activity some 4 km^3 of volcanic debris was deposited on the surrounding countryside.

The catastrophic eruption of Vesuvius on 24 August 79 A.D. is vividly described by Pliny the Younger in two letters to the Roman historian Cornelius Tacitus (Radice 1963). The eruption was pre-announced by several earthquakes that date back to at least 37 A.D. (Marturano 2006). Several volcanological studies have been devoted to the deposits of this eruption, but the one of Sigurdsson et al. (1985) is of particular value because their interpretations correlate with the observations of Pliny. The Pompeii eruption ejected about 3 km^3 of material which is distributed in an area of about 500 km^2 to the S–SE where ash and pumice fell from the eruption cloud, and between SE and W where the impact of pyroclastic surges and flows was the greatest. The main phase of the eruption lasted about 17 hours and its column rose to the height of about 30 km.

The subplinian eruption of 472 produced a plinian column that deposited ash and pumice in the NE directions of Avellino and Benevento. The maximum thickness of these deposits is about 2 m to the NE of Ottaviano and less than 0.2 m in Avellino, 35 km away. After the plinian phase, the volcano produced pyroclastic surges and flows that were directed along the valleys and in the direction of Pollena, in particular, where some deposits are over 15 m thick. Flows from this eruption extend less than 10 km from the volcano and demonstrate an increasing magma-water interaction with time. This subplinian eruption discharged less than 1 km^3 of material and its column rose to the height of about 20 km.

The subplinian eruption of Vesuvius on 16 December 1631 is the most catastrophic event ever recorded in the area. It destroyed many surrounding towns and killed between 4000 and 10,000 people and affected thousands more as they fled from the calamity toward the nearby towns. The eruption produced ash and pumice fall, pyroclastic flows in the form of *nuèe ardentes,* extensive *lahars, tsunamis* in the Bay of Naples, and inundations in Campanian Plain. The eruption began on 16 December around 7 a.m. and it rapidly produced a plinian cloud which expanded high into the atmosphere and spread principally toward the E–NE. The plinian column lasted for about 10 hours before turning into explosions, causing strombolian and lava fountaining activity at the summit. In the morning of 17 December the rain produced flooding of the northern Campanian Plain and violent earthquakes during the night caused the decapitation of the cone of Vesuvius, producing several *nuèe ardentes* which rapidly reached the sea. Most of the surrounding towns were completely destroyed and tens of thousands of people sought refuge in Naples and many thousands in other less afflicted towns. A *tsunami* caused damage in the Bay of Naples as its 2-5-m-high return wave slammed onto the shore. More than 4000 people perished from pyroclastic flows, *nuèe ardentes*, and *lahars*, while thousands more died or were severely injured after the eruption because of building collapses or because they imprudently attempted to walk over the hot volcanic debris. An unknown number of people perished from asphyxiation caused by inhaling volcanic ash, while many escaped death by hiding in buildings from descending pyroclastic flows which flowed around obstacles, such as garden walls, churches, and sturdy buildings. Several days later the volcanic activity subsided, but the volcano continued spitting ash, causing more *lahars* and destruction of the territory. Small earthquakes, strombolian activity, and *lahars* continued into the following years and it took the volcano several centuries to close it magmatic pathways.

From this summary of volcanic hazards at Vesuvius we can deduce several observations. The people should not live within the ‘exclusion zone’ of 4–5 km of the crater, since this zone experiences significant tephra fall loadings (in excess of 4000 kg/m^2) and the buildings can be engulfed by the pyroclastic flows and surges. Between 5 and 8 km of the crater it should, however, be viable to protect some areas with modern technology, or at least protect some of the existing cultural patrimony. Beyond the radius of 8 km of the volcano it should indeed be possible to resettle most of Vesuvians, or construct a sustainable habitat for them. The volcanic material reaching this distance is mostly ash and mud raining from volcanic columns, with roof loadings that do not exceed 3500 kg/m^2, and pyroclastic surges that produce less than about 1 kPa dynamic pressures on the side walls of buildings (Dobran 2001). There is also a hazard associated with ballistic showers (De Novellis & Luongo 2006) and *lahars*, but these hazards are not readily quantifiable at present. A viable quantification of these and other hazards at Vesuvius depends therefore on the tools that can produce the structural loads on buildings and allow for the design of infrastructures. One such tool is Global Volcanic Simulator.

2.4 *Global Volcanic Simulator*

Global Volcanic Simulator is a physico–mathematical–computer model of the entire volcanic system, and as such is useful to produce different eruption scenarios for risk analysis. The simulator incorporates physical and chemical models of all conceivable magmatic processes within the volcano and in the atmosphere above it. It incorporates the geological and geophysical data pertaining to the origin and composition of volcanic deposits, aquifers, rocks and soils, and the strength, elasticity and plasticity of magmas, lavas and surrounding rocks and soils. These data are utilized to produce the mathematical models (constitutive equations) of material behavior at the microscale and macroscale levels at different pressures and temperatures. The constitutive equations are then used in basic physical laws of conservation of mass, momentum, and energy to produce an overall physico–mathematical model suitable for solution on efficient computers (Dobran 1993, 1994, 2006a). The simulator accounts for magma differentiation in magma source regions, propagation of magma toward the surface of the volcano, and mixing and chemical reactions of the material discharged from the volcano with the air constituents.

The magma chamber dynamics model of the simulator simulates the evolution of magma reservoirs for hundreds or thousands of years and forecasts a subplinian or plinian eruption of Vesuvius this century with a high probability. Figure 6 shows a typical output from one such simulation (Dobran 2001). The opening of volcanic conduit model accounts for the conditions of magma in magma reservoir(s) and yield strengths of surrounding rocks and soil, and predicts a very rapid (several days) magma ascent. Several magma ascent models simulate steady-state and transient melting and solidification processes in volcanic conduits. The pyroclastic dispersion model of the simulator can only simulate the axisymmetric propagation of pyroclastic flows around the volcano (Dobran 2001, Dobran et al. 1993), but a much more efficient and useful parallel computer code for 3D simulations of these flows is currently being developed (Dobran & Ramos 2006). This high resolution model will produce the necessary engineering design parameters (pressures, temperatures, velocities) associated with the falls of tephra and ballistic blocks and propagations of pyroclastic flows and surges on small and large structures around the volcano.

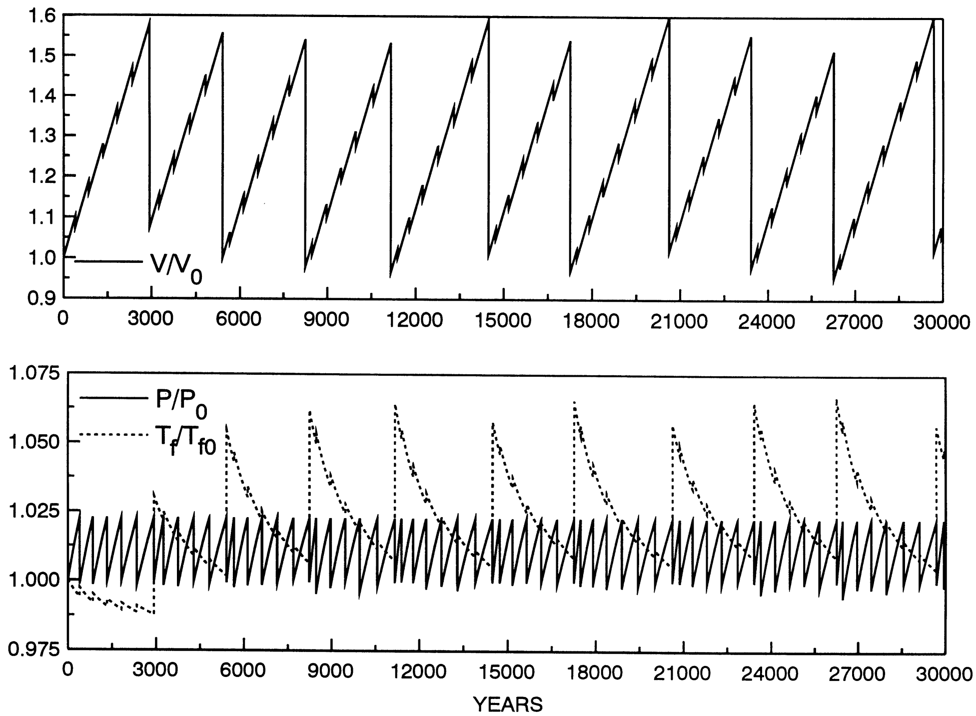


Figure 6. The simulator's magma chamber dynamics model (Dobran 2001) predicts a subplinian or plinian eruption of Vesuvius during this century. Plinian eruptions occur in cycles of several thousand years. Several subplinian eruptions with increasing periods occur between any two plinian eruptions. The results are expressed in terms of the normalized volume, pressure, and temperature of magma in the chamber as a function of time. After several thousand years the initial conditions for simulations do not determine the long-term system behavior.

Predictions from Global Volcanic Simulator can be therefore used to ascertain different eruption scenarios and establish their likelihoods and consequences on the territory surrounding the volcano. Such an all-inclusive physico–mathematical–computer model has been under development since early 1990s and it has produced many useful results (Dobran 2001). These include collapses of volcanic columns and propagations of pyroclastic flows along different slopes of Vesuvius, with and without different size obstacles on these slopes. A large-scale plinian eruption similar to that which buried Pompeii in 79 A.D. produces column collapses and radially propagates pyroclastic flows which in about 2 minutes reach 4 km and in 5 minutes enter the Tyrrhenian Sea, some 7 km from the crater (Fig. 7). Even the 1300-m-high Monte Somma relief to the north of Vesuvius cannot stop these flows. The pyroclastic flows from subplinian eruptions can also cross Monte Somma, while the flows from smaller eruptions cannot and reach the sea in about 16 minutes (Dobran et al. 1994). The results from these simulations are consistent with eruption deposits (Table 1) around the volcano and from 79 and 1631 chronicles (Nazzaro 1997).

A preliminary study aimed at protecting the towns between Vesuvius and the Tyrrhenian Sea is described in Dobran (2001) and the movies from these simulations are available from the author.

According to this work, the subplinian pyroclastic flows of Vesuvius can be stopped while those of plinian eruptions can be slowed down considerably by appropriate obstacles at about 5 km from the crater (Fig. 8). Such obstacles change the direction of flow propagation from radial to vertical and thus produce one or more secondary columns which lift the high temperature material from the flow into the low temperature atmosphere where it is cooled. When this low temperature material falls to the ground it is much less dangerous to the people. Downstream of appropriately designed obstacles we should therefore be able to construct survivable habitats. Many such obstacles already exist on the territory in the form of 6–8 story buildings, but these were not properly designed for protection or for sustaining the loads from pyroclastic flows. When properly designed, these obstacles or barriers can be architecturally and environmentally pleasing structures and parks that are not only useful for safely housing people, but also for protecting the commercial, industrial, and service facilities.

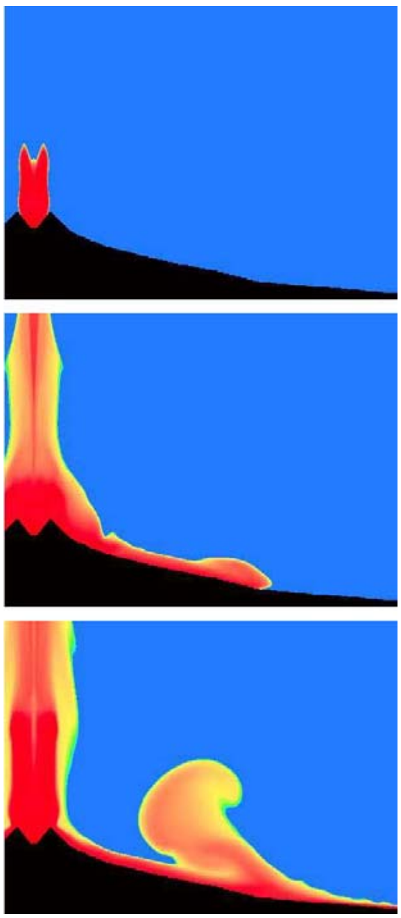
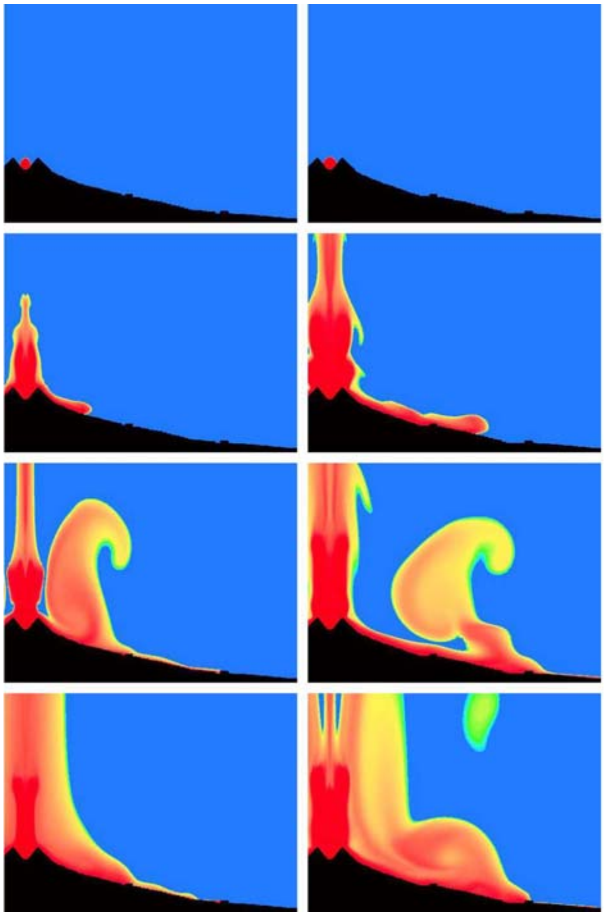


Figure 7. A large-scale eruption of Vesuvius discharges about 10^8 kg/s of material and produces collapses of the volcanic column. The collapsed column produces pyroclastic flows which in about 5 minutes reach the Tyrrhenian Sea. Frames shown correspond to 20, 120, and 300 s after the eruption. The red color denotes high concentrations or temperatures of pyroclasts.



(a) (b)

Figure 8. (a) Pyroclastic flow from a subplinian eruption can be stopped by a 30-m-high obstacle at 5 km from the vent. Frames shown correspond to 0, 30, 300, and 900 s after the eruption. (b) Pyroclastic flow from a plinian eruption can also be slowed down considerably by this obstacle. Frames shown correspond to 0, 180, 300, and 400 s after the eruption.

2.5 *Vulnerability of structures and infrastructures*

The human habitats around Vesuvius are vulnerable to many hazards discussed above. The fall of ash from plinian columns can cause roof collapses of buildings, while the large-size debris from the volcanic edifice can produce severe damage and demolish structures and infrastructures for several kilometers around the volcano. The pyroclastic flows from column collapses can travel along the slopes of the volcano in excess of 200 km/hr and at temperatures from 200 to 500^{o}C, which the humans cannot survive. Any object which is not firmly attached to the ground becomes a potential missile in these flows, while their dense particle concentrations and high temperatures cause death by asphyxiation and burns. Roads and valleys running radially outward from the volcano tend to channel the flows and surges, and any combustible material (vegetation and man-made combustibles) adds to the hazard. Closely spaced buildings provide protection for one another and thus a greater security to the people.

Spence et al. (2004) conducted a survey of existing buildings in the Vesuvius area and employed some results of the pyroclastic dispersion model of Dobran et al. (1993) to assess the vulnerability of these buildings to such flows. They established that building resistances to horizontal pressure loadings are about 4–8 kPa for weak non aseismic reinforced concrete buildings, 7–9 kPa for yellow tuff masonry walls, 6–14 kPa for strong aseismic reinforced concrete buildings, and 20–26 kPa for volcanic masonry walls. The window glasses and old wooden doors can take much less horizontal loadings before breaking, less than 1.5 and 3 kPa, respectively. Petrazzuoli & Zuccaro (2004) employed structural mechanics analysis to determine the horizontal limit pressures of aseismically and non-aseismically built Italian reinforced concrete buildings with one or more floors and examined four different topologies: strong/weak aseismic buildings with the columns containing 1.5/1% steel bars and able to withstand a horizontal force equal to about 10/5% of the dead weight, and strong/weak non-aseismic buildings with the columns containing 0.75/0.35% of steel bars that are unable to resist horizontal loads. The results from the calculations shown in Figure 9 illustrate that the strong/weak aseismic buildings are 2–3 times stronger than the strong/weak non-aseismic ones and that their strengths rapidly decrease with the number of floors. The horizontal loading resistances for most buildings and all topologies considered are always larger than 5 kPa and greater than 10 kPa for aseismic buildings.

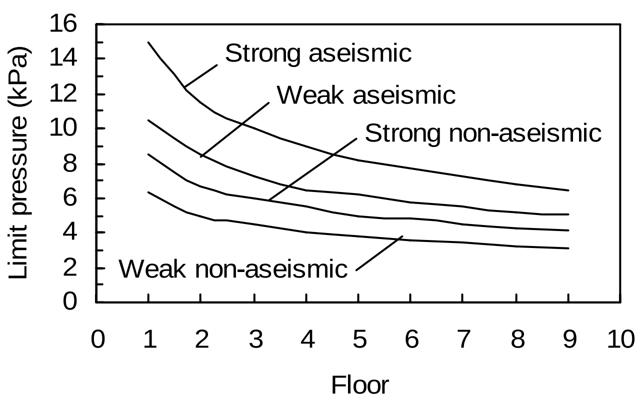


Figure 9. Horizontal limit pressures of strong and weak buildings constructed according to aseismic and non-aseismic building codes. Adapted from Petrazzuoli & Zuccaro (2004).

The dynamic pressures produced by pyroclastic flows from large- and medium-scale eruptions at distances exceeding about 4 km from the vent are less than 2 kPa (Fig. 10). This suggests that the people inside properly designed reinforced structures can be protected at sufficient distances from the crater, but when these structures are breached through the failures of doors or windows the pyroclastic flows cause a rapid loss of life by burns and/or inhalation of ash. Humans survive for less than 15 minutes at temperatures between 150 and 200^{o}C and for less than 5 minutes at temperatures exceeding 250^{o}C.

The 1995 Kobe, 1999 Ismit, and other large and recent earthquakes, have spurred the development of more effective seismological techniques for determining the dynamic parameters associated with the ground motion produced by such earthquakes. The Seismic Zoning technique combines the earthquake information of a zone or region or its synthetic seismographs with the characteristic parameters of the medium through which the seismic waves propagate and produces the location-specific displacement, velocity, acceleration, and frequency content of seismic wave packets (Panza et al. 2001a,b). This methodology can employ broad-band seismic inputs and the available geophysical, geological, and geotechnical characteristics of local and regional areas and thus produce different seismic scenarios which when combined with those produced by Global Volcanic Simulator can be employed for the determination of precise seismic and volcanic loads on the structures surrounding Vesuvius. Panza and co-workers applied such macro- and micro-zonation techniques to ascertain the seismic characteristics of the Italian and Circum Pannonian regions, as well as the local seismic characteristics of Catania, Rome, Naples and other cities (Panza et al. 2002). The earthquakes in Campania can reach $M = 7$ and higher intensities and the Seismic Zoning predicts ground horizontal displacements and their periods as high as 20 cm and 30 s, respectively, velocities and their periods of 60 cm/s and 25 s, respectively, and ground accelerations of about $0.5g$. These are significant seismic loads which the engineers must incorporate into the design of sustainable habitats for Vesuvians.

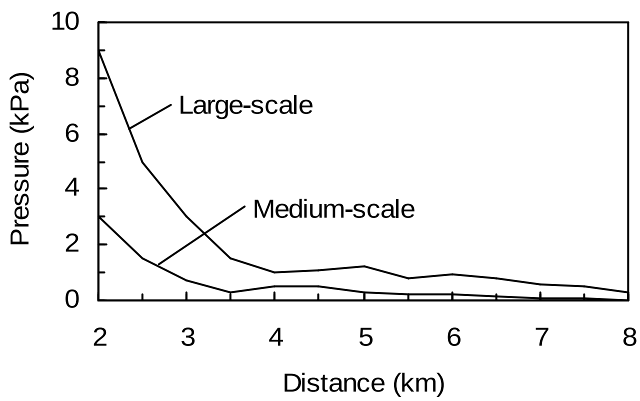


Figure 10. Dynamic pressures produced by pyroclastic flows along the southern slope of Vesuvius at 10 m above the ground. The input parameters for large- and medium-scale eruptions are those as described in Dobran et al. (1994). A large-scale eruption discharges about 10^8 and medium-scale 10^7 kg/s of material.

Most of the buildings and infrastructure of the Vesuvius area have not been designed to withstand significant seismic loads, let alone the dynamic loads produced from tephra fall, ballistic blocks ejected from the volcano, or pyroclastic and mud flows rushing down the valleys and streets of Vesuvian towns. In common seismic designs of structures the energy dissipation from earthquakes takes place in beams and columns, which damages the primary structure even for weak earthquakes. The new seismic design also accounts for the dynamic effects on the structure elements through the so-called response control systems that act as sacrificial elements during seismic, wind, or other types of loadings (De Mattteis et al. 2006). These systems avoid resonances and increase the energy dissipation capacity. They can be implemented as passive, active, or hybrid systems.

The passive systems do not require external power sources, are most common, and can appear in the forms of seismic isolation where the structure and its foundation are isolated from each other, energy dissipation devices that employ hysteretic and/or viscous dampers, and mass effect systems that resonate out of phase with the motions of structural elements. For low to moderate seismic events all structural elements normally remain in the elastic range, while for strong earthquakes the structures may undergo inelastic deformations, with the goal being to design structures that can dissipate large amounts of energy by stable hysteretic behaviors (Ghersi et al. 2006). Instead of using the traditional building strengthening methods (mortar injections, reinforced concrete sandwich panels joined by masonry walls) a different approach consisting of connecting steel bracings to the walls by means of viscous and/or hysteretic dampers can be employed (Mazzolani et al. 2006). The capacity of a structure to the seismic demand can also be increased by reducing irregularity and discontinuity in the distribution mass, stiffness, and strength, or by strengthening some of its structural members. These and other techniques of using steel structures for seismic protection of new and existing buildings, and seismic upgrading of reinforced concrete buildings, are discussed in Mazzolani (2006, 2007), but no accounts are taken in these works of the effects of dynamic loadings produced by different types of volcanic phenomena.

By attempting to reinforce many existing structures in the Vesuvius area with the current seismic code provisions and yet-to-be-determined volcanic code provisions may be both non-economical and technically impossible, because any such upgrading must be cost-effective and sustainable. These are some of the principal reasons why the exclusion zone around the volcano is not worth protecting. Beyond this zone the rehabilitation of structures should, however, be viable, provided that the performance goal parameters derived from seismic and volcanic phenomena can be quantified. Global Volcanic Simulator is a key tool for quantifying many of these parameters, and some of its preliminary results imply that the structures exposed to pyroclastic flows can be subjected to complex dynamic phenomena, such as significant fluctuations of mass flow rates, pressures, and temperatures, even if the material discharge from the vent of the volcano is steady (Fig. 11). This suggests that extreme caution is necessary in constructing or reinforcing any structure close to the volcano, and that the engineers will have an uneasy task of designing and building sustainable habitats for the people living on its slopes.

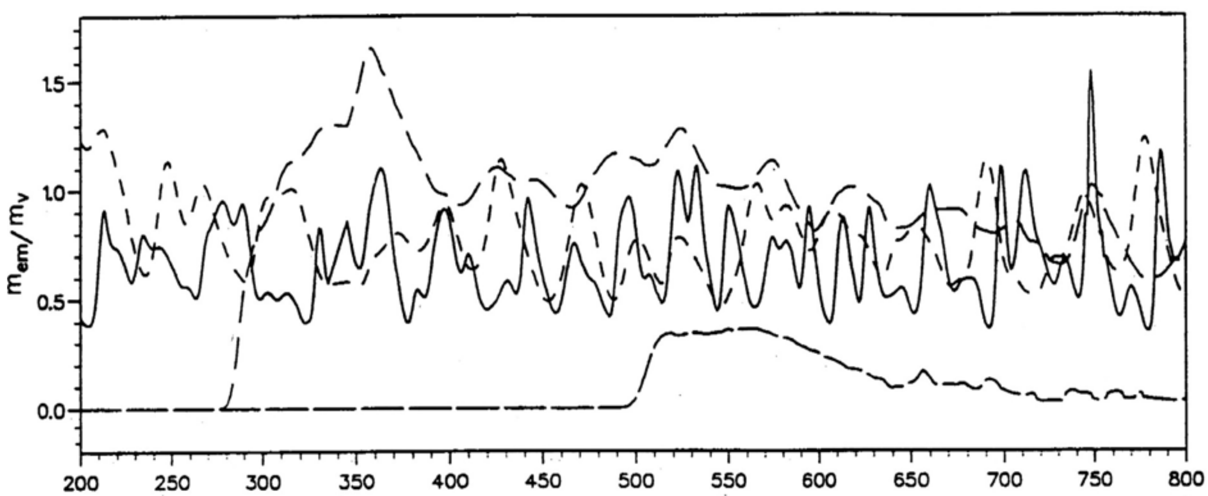


Figure 11. Timewise distributions of pyroclastic mass flow rates normalized by the steady-state discharge mass flow rate of a large-scale eruption of Vesuvius. $R = 3$ (solid line), 6 (short dashed line), 10 (medium dashed line), and 15 km (long dashed line) from the vent. Velocities, densities, and other parameters exhibit similar fluctuations.

We should, therefore, avoid producing more ‘technological fixes’ for this territory, because these have little or no value to the majority of the people. The Vesuvius area is known for such failures, with the Vesuvius evacuation plan and VESUVIA being the two most recent examples (Dobran 2006a). What is needed instead is a value-laden approach to risk management that is based on a proper risk assessment feasibility study involving a multidisciplinary team of experts and the public that intends to benefit from this program. Such a risk assessment procedure requires processing of propositions based on the evidence base we have relative to these propositions, and for this purpose it is useful to employ Bayes Theorem.

2.6 *Bayes Theorem*

Bayes Theorem is important to the risk assessment because it tells us how much our confidence changes when we learn a new piece of evidence. It is a fundamental principle of logical inference that governs the process of evaluating evidence. Thus, if 'A' represents a proposition we are interested in and 'E' represents the evidence we have relevant to this proposition, the probability of given E (posterior probability), $P(A/E)$, is our degree of confidence that A is true after we learn evidence E. Thus,

$$P(A/E) = P(A)\frac{P(E/A)}{P(E)} \tag{2}$$

where $P(A)$ is the probability of A prior to learning E. $P(A/E)$ is, therefore, the revised confidence level of A. In fact, if A_i is one of the events of all possible ones, then

$$\sum_{i=1}^{n} P(E/A_i)P(A_i) = P(E) = 1 \tag{3}$$

and hence $P(E)$ is irrelevant and $P(A_i/E) = P(E/A_i)P(A_i)$. $P(E/A_i)$ is *not* the probability of A_i (though it is of E) and is called the *likelihood* of A_i. Thus the posterior probability is proportional to the prior probability and the likelihood. With any two propositions A_1 and A_2, Bayes Theorem gives

$$P(A_1/E) = P(A_1)P(E/A_1)/P(E), \qquad P(A_2/E) = P(A_2)P(E/A2)/P(E) \tag{4}$$

and thus the *odds* (odds on)

$$O(A_1/E) \equiv \frac{P(A_1/E)}{P(A_2/E)} = \frac{P(A_1)}{P(A_2)}\frac{P(E/A_1)}{P(E/A_2)} = \frac{P(E/A_1)}{P(E/A_2)}O(A_1) \tag{5}$$

represent the ratio of the probability of A_1 to the probability of $\sim A_1$ (not A_1) or A_2. The 'odds against' A_1 are simply $1-O(A_1/E)$ and the *likelihood ratio* is defined as $P(E/A_1)/P(E/A_2)$. If, for example, A_1 represents an eruptive event of Vesuvius producing a pyroclastic flow, Bayes Theorem says that the odds of such a flow, given the evidence E, is the product of the original odds (without E) multiplied by the factor $P(E/A_1)/P(E/\sim A_1)$. The factor is the ratio of the probability of the evidence that the pyroclastic flow occurred to the probability of this evidence that the flow did not occur.

2.7 *Quantitative risk assessment and decision process*

Once the risk scenarios have been identified and their likelihoods and consequences established by using the evidence base via Bayes Theorem, we can perform quantitative risk assessment (QRA) that leads to proper decisions in regard to the management of risk in the Vesuvius area. A decision may, however, require the consideration of one or more options (where and how to build viable habitats) which may affect one or more scenarios and thus their likelihoods and consequences. Each option brings with it costs, benefits, and risks, and our knowledge of these is quantified with probability curves. QRA quantifies these curves and passes the information to the so-called utility curves or value judgments. These may be analyzed as follows.

If d_i, $i = 1,...,n,$ is the decision and A_j, $j = 1,...,m,$ the uncertain event with probability $P(A_j)$, the probability of the consequence X will be $P(X / d_i @ A_j)$ and we can thus compute the utility of decision d_i from

$$\bar{u}(d_i) = P(X / d_i) = \sum_{j=1}^{m} P(X / d_i @ A_j) P(A_j) \equiv \sum_{j=1}^{m} u(d_i, A_j) P(A_j)$$

(6)

We can then choose that decision which produces the largest utility, i.e. $\bar{u}(d_i)_{\max}$. In general, the probability $P(A_j)$ can also depend on decisions made and we should, therefore, write

$$P(X / d_i) = \sum_{j=1}^{m} P(X / d_i @ A_j) P(A_j / d_i) \tag{7}$$

The Decision Theory requires that we perform QRA to determine the outcomes of each option we have and that we assign value judgments for each outcome, so that we can select the best option. Possible options include relocating certain populations from the slopes of the volcano, protecting some areas of the territory, producing economic incentives in certain regions of Campania to attract Vesuvians and thus reduce the demographic load around the volcano, etc. This is a very creative process of the risk analysis problem that requires interdisciplinary data (Sections 3, 4).

Value judgments are the interests of the community, which are normally executed by our representatives in local, regional, and national governments. For example, the Vesuvians may be enthusiastic about the construction of their new habitat because this would bring employment and large resources to the territory, but these people may have very little leverage to convince 50 million or so Italians that this is a worthy enterprise for the nation as a whole. At the present time this utility function appears to be the principal obstacle for seriously addressing the risk around the volcano, but a large earthquake or an eruption can bring about more overpowering and positive-for-the-nation utility functions. The largest utility is the one that leads to an effective decision.

A scenario tree contains in general both the uncertainty and decision nodes, and we can employ the probability theory to compute the odds of different end states and the utilities of different decisions that produce these states. A decision tree analysis leading to the odds of evacuating

Vesuvians on time in the situation of large- and medium-scale eruptions is presented in Dobran (2001). The likelihood ratio of evacuation in 1 week turns out to be about 300, which far exceeds our capabilities of predicting earthquakes where the likelihood ratio is about 1. This implies that such an evacuation is not viable, or that only a long-term preventive strategy (with the likelihood ratio of 10^{-1} or lower) is workable.

The decisions obtained through QRA and based on options and value judgments cannot be properly implemented unless they are also properly communicated to the public. To get a decision accepted and implemented we need the support of the people affected by it, and it is for this reason that the people around Vesuvius must actively participate in producing the correct decisions for the territory. Figure 12 summarizes the procedure discussed above.

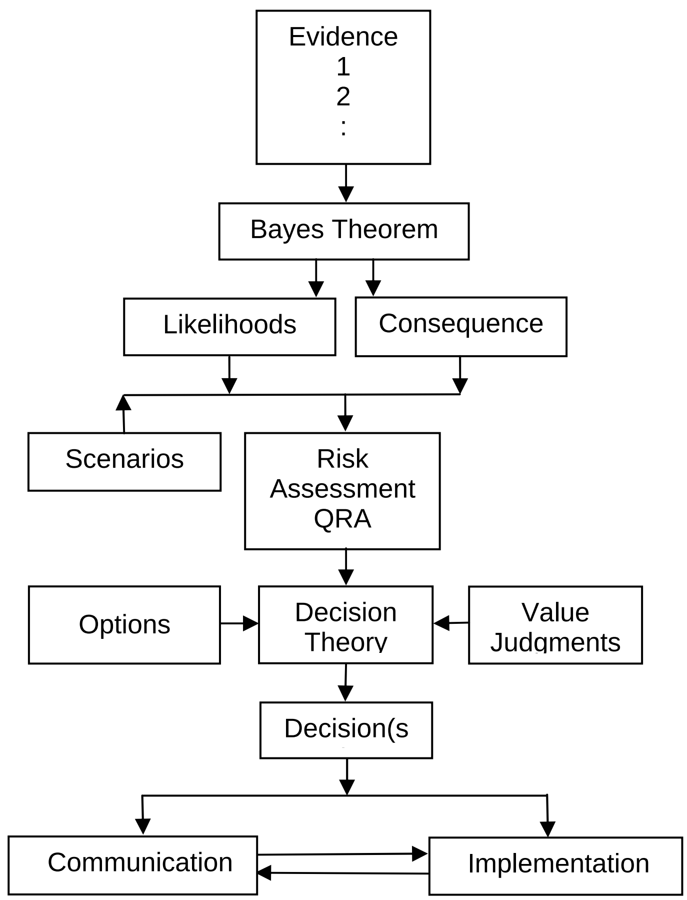


Figure 12. Schematic representation of a risk analysis process leading to decisions, communication, and implementation. Scenarios are determined by using Global Volcanic Simulator and other tools.

Our summary of the procedure involved in producing a viable habitat for Vesuvians left out many details associated with the design and construction of this habitat. The following sections elaborate on some of the important issues and procedures that are associated with this process and set forth a list of objectives that need to be achieved in order to produce proper decisions.

3 FUTURE HABITAT FOR VESUVIANS

3.1 *The grand challenge*

Within the radius of 8 km of the crater of Vesuvius live today more than half a million people under precarious economic conditions and subjected to high levels of criminal activity (Di Donna 2006). We do not have any experience in evacuating so many people on a short notice, and even if they could be evacuated safely somebody would have to provide for their well-being for a long period of time. The host regions would experience economic hardships and political upheavals, and the evacuees themselves would be unhappy, because they abandoned their possessions and their mother land. We should therefore either protect these people from future eruptions or construct a new habitat for them, with improved economic conditions and survivable from future eruptions. To protect all of the Vesuvian territory is, however, not viable, because the first 5 km or so from the crater (the exclusion zone) will be devastated by a large-scale eruption (see data in Table 1). If the majority of the people at greater distances are not moved either, they will have to fear each other more than the volcano. By building one or more sustainable habitats for the majority of Vesuvians at the appropriate distances from the volcano appears to be the only civilized choice in the long run. And by combining the danger from the volcano with the employment opportunities involved in constructing such a habitat, we should indeed produce the necessary fungibility that leads to an effective risk management (Dobran 2006a).

A safe and prosperous habitat for the people surrounding Vesuvius can only be created with the modern technology; with craftsmen, inventors, engineers, scientists, machines, and knowledge gained during the past millennia. Technology offers creative means to control the human built world, and throughout the human history this technology has been used to build great urban centers, protect settlements, advance the standard of living, and challenge the man's creative ingenuity. The Agricultural and Industrial Revolutions have produced cities that are the essential sources of opportunities and the creation of wealth, while their suburbs have been employed to house the working masses and for storing and processing city waste products. Many cities are also dysfunctional because they are not sustainable, or able to meet the needs of the people without compromising the ability of future generations to meet theirs.

To manage the population growth after World War II without expanding the city of Naples, the Neapolitan leaders have banished the working masses into the suburbs with cheaper housing and degraded social services, so that today the 18 communities around Vesuvius have been built on the asphalt and concrete haphazardly or without urban plans, and without accounting for the hazards from the volcano. The once sustainable habitat has been transformed into a degrading social environment where the people have to fear more each other than the volcano itself (Dobran & Sorrentino 1998). And an approach to reduce this fear that is limited solely to building the escape routes can amount to no more than a technological fix which satisfies the exigencies of special interest groups and their cronies. What the Vesuvians need instead is an ecotechnological habitat, because this is sustainable and value laden. Italy is a superb example of splendid models and that the Vesuvians are being denied a secure and prosperous habitat for themselves and their offspring is a tragedy of the Italian leadership which lacks long term visions for the country.

The grand challenge for engineers designing future urban habitat(s) for Vesuvians calls for the understanding patterns of the supply and use of materials, energy, information, services and products, and how to incorporate the protection measures against earthquakes, tephra fall, ballistic blocks, and pyroclastic, lava, and mud flows within these patterns. This knowledge could then be used to select or develop the appropriate businesses, technologies, and levels of protection; build survivable dwellings; and construct the appropriate infrastructures.

3.2 *Urban center design imperatives*

A sustainable habitat is safe from the environmental hazards, but this safety alone does not guarantee sustainability. This is because a sustainable environment also guarantees that the levels of consumption and security are such that they meet basic human needs of food, water, and space, as well provide opportunities to enjoy socio-political rights, health, education, and well-being (Daily & Ehrlich 1999). Another important aspect of social sustainability is equitable distribution of resources. Inequitable distribution of wealth can lead to social instability and disruption (Richard 2002). A socially satisfying environment provides jobs, housing, health care, educational opportunities, community participation, and gives its citizens a sense of belonging and protection. A sense of belonging and pride is already ingrained into the culture of Vesuvians and to preserve these attributes we have to build their future habitat close to the existing one and maintain active small-scale activities, or stay away from designing centers that segregate functions into separate quarters, as common to past practices.

An urban habitat that does not produce irreparable ecological damage and is sustainable must limit its geographical and resources footprints (Fig. 13a). Its area cannot continue to grow indefinitely, for this would exhaust its natural resources and increase the intensity of pollution and waste disposal from the city (Graedel 1999). An urban habitat must also have an ability to adapt to change. It must be efficient in terms of the utilization of resources, provision of education, and control of traffic, and it must be autoregulating in terms of responding to emergency situations. The preservation of large areas of natural ecosystems (such as wetlands) and the utilization of renewable (solar, wind) rather than fossil (coal, oil) energy resources are essential for maintaining sustainability. Education, on the other hand, is essential for making intelligent decisions with high social and ecotechnological contents. One must learn how to behave in crowded environments, reduce pollution, participate effectively in community decisions, and achieve certain level of technological literacy (Dobran 2006b).

A city has both localized and centralized activities, and a manageable urban center should balance such activities. Overuse of personal automobiles brings about traffic congestions and requires allocations of excessive parking spaces, thus increasing pollution, making the city less walkable, and decreasing the efficiency of emergency services. Rather than organizing a city as a complex system one may organize it as complex ‘system of systems’ where the transportation, utilities, recreation, business, and residential neighborhoods are spread across many interconnected clusters with identifying relationships (Fig. 13b) (Gallopin et al. 2001). Walkable neighborhoods reduce congestion and encourage the creation of transportation hubs connecting the city’s components.

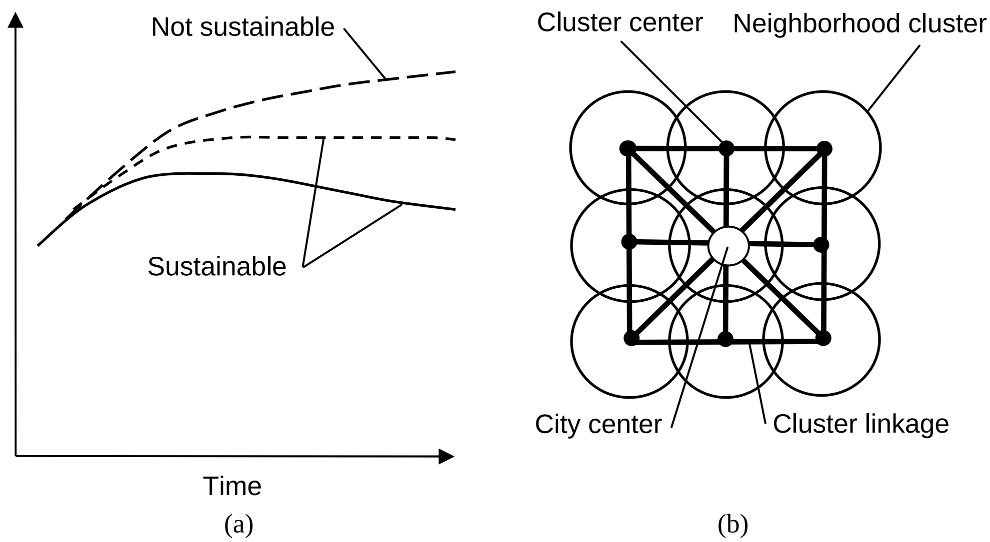


Figure 13. (a) Geographical and resources footprints cannot increase with time. (b) 'System of systems' localizes rather than centralizes the activities, making the city more manageable and livable.

A modern metropolis is a complex bio–socio–machine or 'biosoma', where there is an interaction between the biological component (human inhabitants, vegetation, microorganisms, animals), social component (totality of collective activities, ideas, and organizations of the inhabitants), and machine component (artifacts that support life in the city) (Bugliarello 2002). The biological component is self-replicating and recyclable, and is the source of emotions and knowledge base; the machine component includes precision, reliability, and power; whereas the social component falls in between the biological and machine components. Striking a balance between these components is essential, for neither a totally automated city nor totally run by biological forms is desirable. Both biodiversity and automation enrich our lives, and we should construct future cities that employ these two components. Materials, energy, and information can be used differently within a biosoma, for when all of these interact with the three components above we have an industrial city. But when the emphasis is on knowledge and information we have a knowledge city where the socioeconomic activities generate (universities, schools) and use (business, government) knowledge. When the biological and machine components are integrated and support each other we have an ecoindustrial city where the waste created by one industry becomes the input for another. It is thus the task of city planners to determine what will be the levels of interaction between the biological, social, and machine components, with materials, energy, and information supply or utilization.

3.3 *Engineering challenges*

Urban centers should be designed to meet the needs of tomorrow and they are an integral part of earth systems engineering, because they have impacts far beyond the city borders. Large modern cities are sources of thermal and ground pollution, for they discharge the waste heat into the atmosphere and waste products into the surrounding bodies of water and soil. They easily deplete local water resources, contaminate the ground, and prevent the surrounding wetlands from properly processing the city waste products. And when a large urban center is bordered by natural hazards, such as earthquakes and volcanic eruptions, how can the city dwellers protect themselves from these hazards during an emergency while maintaining the city services and materials and energy supplies functional and telecommunications operational? The overall engineering challenge will be to limit the effects of these hazards and anthropogenic conditions in the city through design and operational decisions. Some of the challenges that the engineers must address are:

1. What are the new paradigms for designing and constructing a sustainable habitat for Vesuvians?

2. How will the stringent environmental and safety requirements of the habitat limit the social, business, and technical options in other sectors?

3. Does the defense from the volcano require new paradigms for urban infrastructure?

4. Is the homeland defensible against all conceivable natural and anthropogenic (terrorism) scenarios, or what risks is the population willing to sustain?

5. What methods of energy supplies and waste disposal and recycling should be employed, and what are the levels of their survivabilities when they are exposed to different earthquake and volcanic events?

6. What kind of habitat should be built (centralized or clustered) and how should this habitat be managed in normal and emergency situations?

7. How will the surrounding natural resources and habitats be affected by the construction of a new urban center for Vesuvians, or should this center become an integral part of Naples itself?

8. What cultural patrimonies in the Vesuvius area are worth protecting and how to protect them?

9. How many people can remain within the exclusion zone of the volcano so that they can be safely evacuated in several hours, and what service facilities, businesses, and infrastructures can be built in its neighborhood without being highly vulnerable to destruction?

10. How to effectively collaborate with the public, national and European Union officials, mass media, and professionals from other fields (urban planners, architects, economists, geologists, environmentalists, social scientists)?

Beyond the engineering challenges there are the political choices that need to be made at the local, national, and European levels, and this is perhaps the greatest obstacle that needs to be overcome before embarking on a serious risk mitigation project for the Vesuvius area. A decade ago a multidisciplinary risk assessment feasibility study for the Vesuvius area was proposed to the European Union (VESUVIUS 2000 1995, Dobran 1995), but it was not supported because ‘the Italian government already has a plan’ (the evacuation plan of geologists).

4 VESUVIUS 2000

4.1 *Objectives*

VESUVIUS 2000 intends to produce guidelines for transforming high-risk areas around Vesuvius into safe and prosperous communities. This would be accomplished through interdisciplinary projects involving engineers, environmentalists, urban planners, economists, educators, geologists, sociologists, historians, and the public. Such a multidisciplinary group of professionals and lay public must work together synergistically, whereby the research and development results from separate groups are integrated into concrete recommendations or guidelines for use by professionals, organizations, and local, national and European Union governments. The central objectives of this project are:

1. Definition of the volcanic system of Vesuvius, and past eruptions in particular, for the purpose of developing physico–mathematical–computer models of the volcano for assessing accurately future eruption scenarios and their likelihoods.

2. Assessment of the vulnerability of population, dwellings, and key industrial, cultural, telecommunication, and infrastructure systems in the Vesuvius area and vicinity for the purpose of establishing cost, benefit, and damage probabilities. This assessment, with and without urban planning interventions, includes medical consequences on the public from the interaction with volcanic products and hazardous materials produced from anthropogenic activities.

3. Development of an educational methodology that promotes Vesuvius consciousness and autoregulation of the territory, for the purpose of establishing new habits of mind that are conducive for the creation of security culture.

The ultimate objective of VESUVIUS 2000 is not only to produce a QRA, or expected human, material, socioeconomic, environmental, and cultural losses in the Vesuvius area from future eruptions of the volcano, but also produce guidelines that minimize these losses and provide an effective collaboration between the experts and the public.

4.2 *Methodology*

Toward the end of accomplishing VESUVIUS 2000 objectives, the project intends to produce the following: Sociological impact statements that identify possible behavior of the population as a result of personal and family danger, and fear of property loss, prior, during, and after the eruptions; economic and territorial impact statements that identify the value on the territory and possible population migrations before and following different eruption scenarios and urban-planning interventions; environmental impact statements that identify the effects of erupted material on the local and regional environments; educational methodologies for producing and maintaining a volcanic risk-conscious population; risk mitigation guidelines for use by the professionals, businesses, public, and local and national administrators; and reports and educational material.

VESUVIUS 2000 is divided into three major interrelated inderdisciplinary areas: Physical environment, population, and territory. The physical environment involves issues directed at quantifying the likelihoods of different scenarios in the Vesuvius area and assessing their consequences on the environment, before and after urban planning interventions. The population involves issues directed at the consequences of the scenarios on the people and property. The territory involves issues associated with Vesuvius area communities, urban planning, environment, and national and European Union governments.

4.2.1 *Physical environment*

Eruption scenarios and their likelihoods are determined from the knowledge of the past behavior of the volcano and by employing such tools as Global Volcanic Simulator (Section 2.4) that can extrapolate this knowledge into the future. The volcanic system of Vesuvius can be divided into different parts or domains, each of which can be characterized by unique properties or characteristic physical phenomena. These parts may consist of magma chamber or reservoir, conduit(s), soil and rock surrounding conduits and magma chamber, and the atmosphere domains. The magma reservoir domain consists of an open system for mass, momentum, and energy transfer between the chamber and its surroundings. Some possible magma chamber processes include multicomponent crystallization, exsolution, melting, and solidification. The conduit domain can be characterized by propagating fractures in which magma exsolves dissolved gases, fragments into pyroclasts, and interacts with conduit walls and surrounding groundwater. The soil and rock domain encloses magma chamber and conduit domains and can be characterized by elastic, plastic, and nonhomogeneous material behavior, depending on temperature, pressure, and chemical compositions of materials within this domain. The atmosphere domain involves a region where the volcanic products mix with the gases in the atmosphere and interact with people, dwellings, and infrastructures on the slopes of Vesuvius. Physical and chemical processes in each of these domains have different temporal and spatial scales and thus require appropriate physical modeling considerations and numerical techniques for solving the resulting set of mathematical equations. The effectiveness of simulating all relevant volcanic eruption scenarios depends on the effective combination of different domains into Global Volcanic Simulator.

4.2.2 *Population*

More than half a million Vesuvians are highly vulnerable and a significant effort needs to be directed at these people with the objective of changing their negative habits. This population is largely uneducated about the potential danger from the volcano and how to avert it. During the preparation of VESUVIUS 2000 objectives in 1994 and 1995 we were fully confronted with this problem and the lack of collaboration from many scientists and public officials. Such widespread negative attitudes, behaviors, and mentalities act in detriment to the public, and scientific and cultural progress, in particular. An effective risk mitigation in the Vesuvius area requires, therefore, confrontations with these realities, or with very complex personal, political, and socio-economic interests that are impeding serious work on reducing the risk. It is, therefore, necessary to approach this problem with an open mind, and above all from an interdisciplinary perspective, with the central objective being to develop new habits of mind that are conducive to collaboration.

The vulnerability of a territory depends not only on its physical parameters, but also on the knowledge of local communities and behavior of local decision makers. Any actions directed at reducing this vulnerability should confront how to transform acquisitions from experts into diffuse knowledge of communities and how to induce local decision makers and apply recommendations from the experts. The demographic pressure in the Vesuvius area is enormous, the efficiency of the government on the territory is weak, the credibility of public administrators is, in general, very scarce, and the volcano is quiescent. This implies that by utilizing the traditional methods of sensibilization may not contribute significantly to the building of

Vesuvius consciousness and that an effective consciousness of the volcano needs to be produced through the decision makers who utilize the territory to satisfy their own personal exigencies.

The principal objective of a socioeconomic study should be to analyze the whole territorial settlement on the Campanian Plain for the purpose of providing detailed geographical data related to population dynamics, housing and real estate property, facilities, and public services. An analysis of population dynamics should include demographic studies of natural and migratory flows at the regional, municipal, and submunicipal levels, whereas a real estate property analysis should include private properties (number of rooms, crowding index, building periods, housing quality) and public buildings (offices, schools, hospitals, museums, military buildings, and historical, artistic, and archaeological sites). These data should then be used to construct a synthetic index regarding the real density of each municipality and use destination of the territory which is split into rural, urban, protected, and facilities areas.

Education is fundamental in producing a Vesuvius conscious population and a security culture of tomorrow. It is therefore necessary to: Establish links between different educational groups operating on the territory for the purpose of exchanging information, eliminating duplication, and establishing collaboration; analyze existing volcanic risk educational methodologies in primary, intermediate, and secondary schools through seminars and group discussions; identify effective volcanic risk educational methodologies pertaining to different age groups of children and adults; identify negative habits of mind and produce strategies aimed at overcoming barriers for adopting new habits that are conducive to the creation of a Vesuvius-conscious public; prepare educational material for school children and adults and dissemination of this material on the territory; involve the public in coauthoring volcanic risk mitigation guidelines; and train educators and territorial administrators for diffusing correct information on the territory.

4.2.3 *Territory*

The territory includes environment, energy and water supply, water and waste disposal, telecommunication, transportation, recreation, socioeconomic and political policies of population management, civil protection volunteers, and so on. This systems study should employ a Geographical Information System for the purpose of integrating this information with eruption scenarios.

Urbanization is the most powerful and most visible anthropogenic force which invests the territory. The surface ‘footprint’ in the Vesuvius area consists predominantly of human habitats and concrete (or asphalt). These deprive supply of water, space to construct employment and service facilities, space for waste disposal, and land for cultivation of crops and enjoyment of recreational activities. Because the Vesuvian habitat of the future should be an essential source of opportunities for social and cultural advancement, it is essential that this be environmentally and socially sustainable. The urban plans that need to be developed must account for the needs of tomorrow. This is a grand challenge for engineers and urban systems planners (Sections 3.1, 3.2). It is a challenge to produce those urban plans that integrate an emotionally satisfying place to live with effective use of human and natural resources and technology and management system structures with the public playing a central role in decision making. All of these characteristics must interact synergistically in order to reduce future risks from Vesuvius, minimize pollution from transportation systems and industry, improve livability, and endure sustainability. These goals call for urban systems simulations involving land use utilization and transportation management that make up the Vesuvius area communities which interact with the rest of the territory and with the city of Naples, in particular. The future habitat of Vesuvians must be respectful of its environment even if the volcano is quiescent. The emissions of hazardous chemicals and greenhouse gases into the atmosphere, soil, and water must be limited and these limits must be enforced through the regional or national environmental protection agencies. These emissions should also enter into the quantitative risk assessment for the territory.

Civil protection volunteers are an important part of risk management, for in the event of an emergency they (through their knowledge of local population and its culture) can provide most of the aid at the beginning of a calamity. This situation occurred during the 1980 earthquakes and 1998 mudslides in Campania, because the central bureaucracy of *Protezione Civile* was inefficient in dealing with the unexpected calamities. For volunteers to be effective it is necessary to involve them in planning of emergency services and emergency needs. What use is emergency planning if it is being hidden from the public and not being available to the public and independent professionals for evaluation? The responsibility for such a planning resides with the regional government of Regione Campana.

4.3 *Decision process*

The systems studies proposed on VESUVIUS 2000 must be integrated through a quantitative and visceral risk assessment methodology as discussed in Section 2.7 and summarized in Figure 12. Following this feasibility study enough resources should be secured to begin transforming the Vesuvius area and vicinity into safe and prosperous communities. But this will not occur until the communities around Vesuvius begin seriously collaborating among themselves and with those who are capable of achieving the objectives of the grand challenge. We have the technology and human capital to meet this challenge, but lack the volcano-conscious public which can take advantage of the danger and transform this danger into an asset. Further elaborations of these and other issues, methodologies, and accomplishments of VESUVIUS 2000 can be found elsewhere (Dobran 1998, 2001, 2006c).

5 CONCLUSION

In this paper we have discussed some of the issues involved in assessing the environmental risk around Vesuvius and argued that a sustainable habitat should be constructed for the majority of the people living in the immediate surroundings of this volcano. This habitat must be both secure from future eruptions and socio-economically viable center with proper interactions between the people of different social classes and the modern technology. Materials, energy, information, and natural and anthropogenic hazards must all enter into the design of this habitat, and for the engineers and other professionals its design and construction form a grand challenge without precedence. The professionals must discover new urban planning and protection paradigms and the mental barriers of those who are remaining passive to the Vesuvius problem must be overcome. We have the technology and human capital and an extraordinary opportunity to begin working on a serious project. There is no time to waste, because Vesuvius is preparing to reclaim its territory.

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