A lava flow simulation model for the development of volcanic hazard maps for Mount Etna (Italy)

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Abstract

Volcanic hazard assessment is of paramount importance for the safeguard of the resources exposed to volcanic hazards. In the paper we present ELFM, a lava flow simulation model for the evaluation of the lava flow hazard on Mount Etna (Sicily, Italy), the most important active volcano in Europe. The major contributions of the paper are: (a) a detailed specification of the lava flow simulation model and the specification of an algorithm implementing it; (b) the definition of a methodological framework for applying the model to the specific volcano. For what concerns the former issue, we propose an extended version of an existing stochastic model that has been applied so far only to the assessment of the volcanic hazard on Lanzarote and Tenerife (Canary Islands). Concerning the methodological framework, we claim model validation is definitely needed for assessing the effectiveness of the lava flow simulation model. To that extent a strategy has been devised for the generation of simulation experiments and evaluation of their outcomes.
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Keywords: Volcanic hazard; Lava flow simulation model; Geographical information systems

1. Introduction

Volcanoes may generate a wide variety of phenomena that can endanger environment, people and civil infrastructures. It is therefore of primary importance for the government authorities to develop comprehensive land use and emergency plans that safeguard the resources of the territory exposed to volcanic hazard. Volcanic hazard maps constitute the most common way for representing the geographical areas that may be affected by a dangerous volcanic event, such as pyroclastic flows and falls, lava flows and lahars. Typically, the map divides the volcanic region into a number of zones that are differently ranked based on the probability of being damaged in a given period of time by a specific volcanic event. Despite the apparent simplicity of the map, however, the process leading to the identification of the hazard zones is very complex and generally little structured.

In order to provide a more systematic approach to the development of hazard maps, simulation models of the eruptive process can be very helpful. In this paper we discuss the characteristics,

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application and testing of a lava flow simulation model meant to support the development of a lava flow invasion hazard map for the Mount Etna (Sicily, Italy).

Etna, with an altitude of 3323 m, is the most active volcano in Europe. There have been frequent eruptions not only in the past but even in recent times, mainly consisting of basalt lava flows (Azzaro and Neri, 1992; Behncke and Neri, 2003). Moreover, numerous towns and important economic activities are located nearby and on the flanks of the volcano, so that a lava flow hazard map is definitely needed. Nevertheless the only hazard maps that have been realized so far for Mount Etna go back to twenty years ago and are based on incomplete knowledge of past eruptions and only qualitative analysis (Guest and Murray, 1979; Duncan et al., 1981; Forgione et al., 1989). Recently Chester et al. (2002) have published a paper reporting the state of the art on volcanic hazard assessment, showing for the Etna volcano the map of Duncan et al. (1981).

To address the need of a more accurate hazard map of Mount Etna, we propose an approach based on the combined use of detailed geological and stratigraphical data, stored in a Geographical Information System (GIS), with a quantitative and probabilistic lava flow model simulating the lava flow originated from an emission point. The GIS is an extremely helpful tool for volcanic hazard evaluation because it can directly and immediately support semiautomatic or automatic data processing (Pareschi et al., 2000; Groppelli et al., 2001; Bertino et al., 2003). Moreover it ensures a more systematic evaluation of hazard parameters. On the other hand, the simulation model enables the estimation of the areas that could be invaded by lava. A remark to be done is that, unlike other approaches existing in literature, such a model is not meant to support real time forecasting but rather the assessment of the lava flow hazard in the medium-long term. Therefore it simulates average future lava flows in a way that is not strictly related to the physical characteristics of the effusive eruptions (Kilburn, 2000).

The major contribution of the paper is twofold: (a) a detailed definition of the underlying simulation algorithm; (b) the definition of a methodological framework for applying the model to the specific volcano. With respect to the former, we propose an extended version of the stochastic model developed by Araña et al. (2000) and Felpeto et al. (2001). Such a model has been applied so far only to the volcanoes of the Canary Islands, but to our knowledge the model has not been validated against past eruptions. Conversely we believe that the validation of the model is a crucial task to prove the effectiveness of a simulation model. For that purpose a validation strategy is required, which we propose in this paper for Mount Etna. The paper is structured as follows: we provide first an overview of the most significant approaches to lava flows simulation. Next, we introduce the methodology we have devised for the development of the simulation model focusing on: the data sources that we have used; the algorithm that has been developed by extending the original proposal with new features; the description of how the model has been applied to Mount Etna. We conclude with a presentation of the implemented software system and with final remarks about the overall methodology currently under development for the construction of the lava flow hazard map.

2. Lava flow simulation: related work

Varieties of models have been proposed for the simulation of lava flows. Some approaches are based on the physics of the phenomenon, others on probabilistic models.

Ishihara et al. (1989) have proposed a pure deterministic model, whereas Wadge et al. (1994) have developed a model combining deterministic and probabilistic methods. Barca et al. (1987, 1994, 2004), Miyamoto and Sasaki (1997), Crisci et al. (1982, 2003), Avolio et al. (2004) have instead developed techniques based on cellular automata. Recently Vicari et al. (2004) have proposed to use cellular neural network to simulate lava flow paths (2001 and 2002 eruptions). With respect to the reliability of predictions, the current deterministic models have reached a high degree of sophistication. However, they are difficult to apply for hazard assessment because they require the detailed specification of numerous parameters, referring to the physical properties of the eruption and its evolution, such as lava flow rate, lava viscosity, temperature and ephemeral vent locations, that are often not available, difficult to predict and vary depending on the eruption. Moreover, if the knowledge of these parameters is incomplete the simulation outcome may be unreliable. The other category of models is the probabilistic ones. In general, these models rely on a simpler set of parameters. Several probabilistic models have been developed in the last ten years

such as the model applied during the 1991–1992 eruption of Mt. Etna to evaluate the most probable paths of the lava (Barberi et al., 1993; Dobran and Macedonio, 1992) and the models proposed by Macedonio (1996) and Felpeto et al. (1996) which simulate the lava flow path based on the maximum slope.

For the development of the hazard map, we believe that a probabilistic model is a more viable approach because of the difficulty to evaluate all the parameters required by deterministic models.

A probabilistic model that seems promising for the construction of the hazard map is the one developed by Araña et al. (2000) and Felpeto et al. (2001) (hereinafter called Felpeto's model). In such a model, the simulated lava flow consists of a geo-referenced grid of cells, each cell of which is assigned a value indicating the likelihood of lava coverage. The probability distribution results from the computation of the most probable lava flow paths and it is strongly dependent on topography.

The Felpeto's model however has been applied only to the evaluation of the hazard of the Tenerife and Lanzarote volcano (Canary Islands) (Araña et al., 2000; Felpeto et al., 2001). In order to prove the effectiveness of the model in the case of Mount Etna, we have first developed an extension of the original algorithm (ELFM — etna lava flow model), then we have validated the model by comparing the outcomes of the simulations against past lava flows.

More specifically the entire process of development of ELFM has been subdivided in three phases, that are detailed in the rest of the paper:

1. Data acquisition and organization;
2. Model specification and software implementation of the simulation algorithm;
3. Validation of the model applied to the Etna volcano.

3. The Etna Lava flow model: the data sources

A key aspect of the proposed approach is that it does not require many different types of data and yet, as we will discuss later on, it provides an accurate modelling for the estimation of the lava flow hazard. In particular, our approach relies on the following data types:

(a) The digital topography of the volcanic region in the form of digital elevation model (DEM);

(b) Geological data about the past eruptions.

Data have the following characteristics:

(a) The DEM is based on a topographic vector dataset going back to 1986 provided by the National Volcanology Research Group (Gruppo Nazionale Vulcanologia—CNR) (Fig. 1). The size of the cell is 10 m while the projected coordinate system is Gauss-Boaga with Datum Rome 1940.
(b) Geological data are derived from the Acireale Sheet Map (Servizio Geologico d'Italia, in press), a new geological map at scale 1:50,000 of the eastern flank of Mount Etna. The Etna volcanic activity started about 500,000 years ago (Gillot et al., 1994). In the Acireale sheet map the authors have distinguished lithostratigraphical units, usually formation in rank. The most recent products belong to the Torre del Filosofo formation (last 15,000 years) and cover 85% of the Acireale Map. In the recent succession, approximately 130 lava flows have been identified and mapped (Branca et al., in press).

The geological data, along with spatial and temporal information, have been properly organized in a geographical database. For each lava flow the following properties are recorded in the database: emission points, eruptive fractures, related spatter and/or scoria cones, age, (planar)
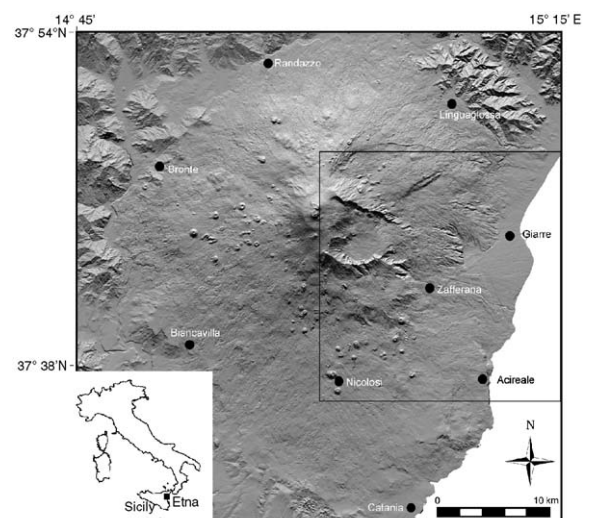

Fig. 1. Shaded image of digital elevation model for Mount Etna. Box highlights extent of Acireale Sheet Map, that is area of interest.
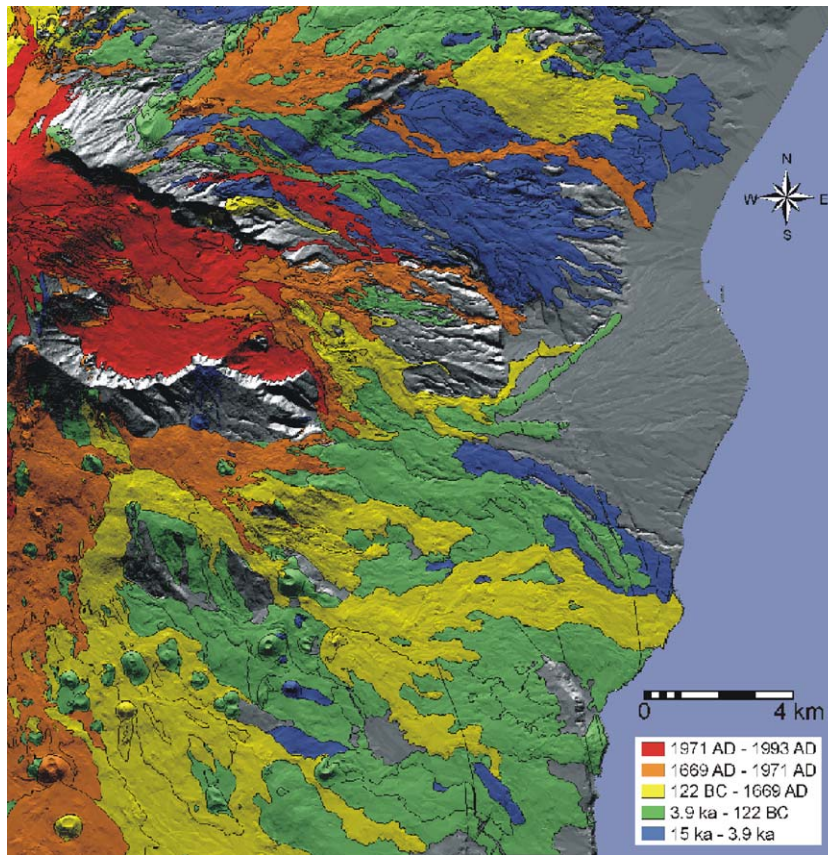
Fig. 2. Lava flows distribution related to last 15 ka (Mongibello Volcano). Representation is based on five lava flows time interval. Gray areas are related to old lava succession or to talus (modified from Branca et al., in press).

length and the actual extent. On the Geological Map at 1:50,000 scale the authors have grouped all the recent lava flows in five time intervals limited by important eruptions in the last 15,000 years of Etna activity (Mongibello volcano) (see Fig. 2).

4. The Etna Lava Flow Model: the algorithm for lava flow simulation

We now discuss the algorithm for the simulation of the lava flow. For an easier comprehension, we introduce the algorithm stepwise presenting first the essential features of the Felpeto's approach and then how it has been extended.

In the Felpeto's model, the basic parameter is the grid representation of the topographic height (i.e. the DEM). Given a DEM and an emission point, the algorithm iteratively computes a number of paths for the lava flow and then assigns each point of the region the probability it will be invaded by the lava flow.

The single path is computed stepwise: at each step, starting form the emission point, the lava propagates from the current cell to one of the adjacent cells. The next cell in the sequence is selected by first assigning a slope-dependent probability to the eight neighbouring cells and then randomly selecting one of the candidate cells for which that value is positive. More formally:

Consider a cell c where the lava flow is currently located. The probability P_i that the flow enters into one of the eight surrounding cells c_i ($i = 1, 2, \ldots, 8$) can be expressed as follows:

$$P_i = \frac{\Delta h_i}{\sum_{J=1}^{8} \Delta h_j},$$

where Δh_i is the difference in height between the cell c and the neighbouring c_i.

In the computation of such a difference, however, the height of the cell c is increased by a corrective

factor δ to allow the lava flow to propagate over arbitrarily small topographic barriers. The factor δ is important because it models the lava flow thickness. It represents one of the parameters of the algorithm. As we will see, whilst in the Felpeto's model such factor is assumed to be fixed for the whole duration of the computation in our approach such value is dynamic.

The computation of the path terminates when one of following cases holds:

(a) the height of the cell covered by the lava flow is lower then the height of the sixteen surrounding cells;
(b) a maximum number of cells have been computed;
(c) the prosecution of the path is physically impeded (for example, the path has reached the border of the map).

4.1. Preliminary definitions

We now reformulate more formally some of the above concepts:

- Grid: a grid of squared cells covering a geographical region. It is defined by:
- o number of rows N and columns M of the grid;
- o size of the cell;
- o location of the grid.
- Grid function: a function $f: Gr \rightarrow Dom$ that maps a grid Gr onto a domain Dom of numeric values. Function f assigns a value to each cell of the grid. The function may be represented as a matrix of numeric values.
- DEM: a grid function assigning each cell of the grid an altitude value. The value associated with a cell is the height of the cell.
- Lava path: intuitively it is a sequence of cells invaded by the lava flow. More precisely a lava path can be defined as follows. Given a grid g, a path p in g consists of:
- o A sequence s of cells belonging to g: $s = <c_0, c_1, ..., c_{last}>$, where c_0 is the emission cell or point and c_{last} the last cell computed by the algorithm. The cardinality of the sequence (i.e. the value of the last index) indicates the length of the path p.
- A grid function F defined over the same grid g, such that $F(c_i) = 1$ for each i such that $c_i \in s$, otw $F(c_i) = 0$.

- Lava flow height: a grid function assigning each cell the value of the lava thickness in that cell.
- Current cell and Destination cell: the current cell is the last cell invaded by the lava during the computation of a lava path; the destination cell is the cell immediately following the current one in a path or null if the current cell is the last of the path.

4.2. The simulation algorithm

Finally, we introduce the simulation algorithm. It extends the Felpeto's approach by introducing two new concepts described in detail in what follows: dynamic DEM and variable lava flow height.

Dynamic DEM. A phenomenon that may occur in the original algorithm is that the lava flow path propagates backwards moving to the cell it originated from contrarily to what naturally happens. The consequence of this phenomenon, referred to as flow loop, is that the lava might propagate along unnatural paths.

We have noticed that such a phenomenon may occur when the height of the current cell is close to that of the adjacent cells. More precisely:

Let h_c be the height of the current cell c of the path p, δ the corrective factor, h_i the height of the destination cell i. If the following conditions are both true:

(a) $h_c + \delta \geqslant h_i$,
(b) $h_c \leqslant h_i + \delta$,

that is, in more compact form

$$|h_c - h_i| \leqslant \delta.$$

Then the flow might propagate from the current cell to the destination (a) and then back again to the previous one (b).

In order to reduce the probability of flow loop, the algorithm has been modified. At each step, when the flow propagates from the current cell c to the selected destination cell i, the height h_c is modified and increased of the corrective factor δ, as follows;

$$h_c \leftarrow h_c + \delta.$$

It can be noticed that this simple heuristic accounts for an obvious fact, that the height of cell c is increased by the height of the lava flow invading c. In other terms, the topography in a point is dynamically modified because of the lava flow. Therefore the DEM can be considered as being

dynamic. Moreover in case the lava flow has reached a sink, so that the current cell is surrounded by higher cells, the height of the lava flow in that cell may increase up to a maximum value MaxH. The following terminating condition has thus been added to the algorithm:

$$\Delta h_c > \text{Max } H$$

where Δh_c is the lava flow height in the cell c.

Variable lava flow height. The second concept accounts for the fact that the thickness of lava flow may vary depending on the physical properties of the lava flow and the topography ([Walker, 1973](#); [Cas and Wright, 1988](#)). While a constant value may be a reasonable assumption when the lava flow height is relatively low (a few metres), the same does not hold when the lava flow may reach 10–30 m. In such a case, in fact, a fixed value would cause the undesirable propagation of the lava flow along unnatural paths.

In order to address this requirement, we have introduced an additional parameter specifying how the lava flow height would vary. The value of such a parameter is a mathematical function; in the simplest situation, it is a constant function.

The effect of such a parameter on the simulation will be discussed in the next section.

4.3. Summary of specifications

A detailed specification of the algorithm is reported in an appendix to the paper. In this section we only summarize the input and output parameters of the algorithm as referred to in the next section. For what concerns the input data, the basic parameters of the algorithm are:

- G: the grid of the volcanic region. It is the grid superimposed over the volcanic region.
- Dem: the DEM of the volcanic region. It is the matrix of altitude values associated with the grid G.
- Ep: the emission point, that is, the starting point of the lava flow; it is a cell of the grid G identified by the local to the grid coordinates (row, column).
- MaxL: the maximum number of cells in a single lava path.
- MaxH: the maximum height of the lava flow.
- F: the function expressing the variation of lava flow height.
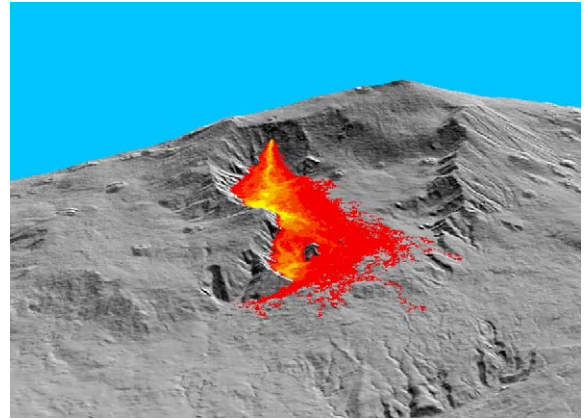- Iterations: the number of paths to be generated.

Fig. 3. Simulated lava flow in Valle del Bove (Esri ArcScene). Picture displays simulated lava flow draped over perspective view of DEM. Different colours for lava flow are used to highlight different number of lava paths passing over points of region. Yellow pixels, opposed to those marked in red are those that are more frequently overrun by lava paths.

Notice that the model requires the knowledge of the maximum number of cells and the lava flow height which are parameters related to the characteristics of lava flows. These values specify the terminating conditions for the algorithm: in particular they indicate when the lava paths stop. It can be noticed that in the Felpeto's algorithm, the termination problem is solved in a simple way, since the lava flow is assumed to propagate up to the natural barrier represented by the sea. In our model, we assume instead that such values are provided by some preliminary estimation based on past lava flows. We will come to this point later on in the final section regarding the general methodology proposed for the development of the hazard map.

Concerning the output parameter, the basic parameter is the *Flow* matrix. It is a grid function defined over the same grid G. Such function assigns each cell the percentage of lava flow paths overrunning the cell. Such value will be 1 at the emission point and of course 0 in the cells that will never be reached by the simulated lava flow.

The implementation of the simulation algorithm is quite straightforward. An example of the algorithm results is reported in [Fig. 3](#).

5. Validation of the simulation model

The last and most crucial step of the whole process is represented by the model validation which should assess the effectiveness of the

simulation model and ultimately the reliability of predictions. Since the only knowledge we have is about the eruptive events which occurred in the past, the strategy we propose is based on the comparison of simulation outcomes against past lava flows paths stored in the geological database. The reasoning is of inductive type: if we can show that simulations can approximate the past lava flows then it is reasonable that the model is also able to predict the path of future lava flows.

Seemingly, the proposed strategy is simple, nevertheless there are some aspects that need to be more precisely defined. First, we need to define exactly what is the subject of comparison; in other words which features of the lava flows are to be compared. We have devised two possible approaches: the first directly derives from the Felpeto's approach. In such a case the basic assumption is that the outcome of the simulation would represent a spatial distribution of probability, that is the value $p \in [0,1]$ assigned to a cell would indicate the probability of lava invasion in that cell. Therefore, the comparison should evaluate the probability distribution of the simulated lava flow against the historical lava flow. However, from the experiments it turns out that the average probability assigned to lava flow cells would be quite low (<0.4) even in correspondence to the actual coverage. That makes sense, since, for how the algorithm is defined, the lava paths propagate in different directions and thus the frequency with which lava paths overrun the same points is generally low especially where the slope of the terrain is limited. It is thus difficult to establish a threshold for the probability to be meaningful. These considerations have led us to adopt a different approach that is based on the following assumption: the set of cells of the simulated flow, independently of their value, shape the extent of the predicted lava flow. Accordingly, the comparison of the lava flows can be reframed in terms of a geometric comparison between the historical and the simulated coverage. We have thus introduced an evaluation criteria stating that a necessary condition for the matching between a simulated lava flow and the historical lava flow originated from the same point to be satisfactory is that the extent of the simulated lava flow geometrically covers the historical extent.

In order to apply this strategy, we have selected a limited number of lava flow samples (see Fig. 4). Specifically, in the paper we refer to the eruptions of 1792, 1971 and 1991. These eruptions have been selected because their coverage can be precisely
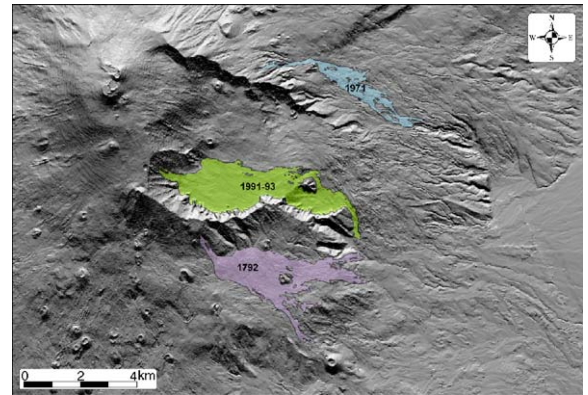

Fig. 4. Historical lava flows: 1971 (blue), 1991 (green), 1792 (purple).

outlined and also because of the topographic and geological characteristics of the lava flows. Specifically, the 1792 eruption produced a large mainly tube fed pahoehoe lava flow field about 6.5 km long flowing south-eastward from 1900 to 610 m a.s.l south of the Valle del Bove depression. The 1971 eruption generated a 7 km long aa lava flow extending eastward from 1840 m a.s.l. north of the Valle del Bove depression. Finally, the 1991 eruption produced a wide lava flow field of 8.75 km flowing eastward within the Valle del Bove depression; it was a complex aa flow field characterized by several tubes and tumuli development and rootless emission points (Calvari and Pinkerton, 1998; Branca and Del Carlo, 2004).

We examine now in more detail which values have been assigned to the parameters of the algorithm for generating the simulation from the three emission points.

5.1. Parameter tuning

The relevant parameters which have to be considered are:

- Iterations.
- Max$H$.
- Max$L$.
- F.

The criteria used for assigning such values are presented in what follows:

Iterations. With respect to the number of paths to be computed, we have verified that increasing the number of iterations over 1000 would not appreciably change the simulation results.

Table 1
Data input values for parameters Max$H$ and Max$L$ used for simulated lava flows

Lava flow	1792	1971	1991
Max$H$	15 m	10 m	37 m
Max$L$	5800	3000	6000

MaxH. In order to assign a value to the parameter, we have generated multiple simulations using different values of Max$H$ and then selected a good fitting value.

MaxL. The estimation of parameter Max$L$ (maximum number of cells in a single path) is quite complex because the length of the lava path is expressed in term of cells and such number depends on several factors that are difficult to predict, first of all the topography. Moreover, we have found only a qualitative relationship between the maximum number of cells of the lava paths (Max$L$) and the maximum linear extent of the flow. In fact, Max$L$ accounts for the maximum number of cells occupied by a single lava flow path, independently on the direction of such a path. For example, in a flat area, it can be shown that lava paths tend to expand with limited advancement. To obtain the value of the parameter, we have thus generated simulations with different values of Max$L$ and then selected a good fitting value.

The values of the two above parameter for the three lava flows are summarized in Table 1. As it will be discussed later on, we intend to rely on past eruptions to determine reference values for the above parameters. Hence, based on those values, future lava flows originated from potential emission points should be generated.

The function F. Finally, we consider the tuning of the parameter *F* modelling the variation of lava flow height. Since initially it was not clear whether such a parameter would have affected the simulation, we have generated a number of tests using different values for *F*. Specifically, we have run the simulation model with three functions defined as follows:

The main result of this analysis is that the function F affects the simulation especially nearby the emission point. In Figs. 5–10 we report a few simulations of the eruption of 1991. They have been generated using different values for F and different path lengths (Max$L$), whereas the maximum lava height (Max$H$) has been kept constant. Specifically the parameter value is set as follows: simulations in Figs. 5 and 6 have been generated using function (a); those in Figs. 7 and 8 are based on function (b); and finally those in Figs. 9 and 10 are based on function (c).

If we look at Figs. 5 and 6 (i.e. constant lava flow height), we can notice that in proximity of the emission point the simulated lava flow extends approximately 200 m. beyond the actual coverage. That is due to the fact that the thickness of the lava is so high even in proximity of the emission centre that the lava flow can propagate in many directions.

In Fig. 7 (i.e. linear lava flow height) we notice a closer matching. However, when the number of cells is higher (Fig. 8) the shape of the lava flow gets exceedingly thin. That is because for how the function F is defined the lava flow cannot expand around. In Figs. 9 and 10 (i.e. logarithmic lava flow height) the simulation results are close to the previous two but apparently better than when a fixed value for the lava flow height is used.

What ultimately results from these tests is that the assumption of a fixed value for the lava flow height would lead to a coarser approximation. A variable value in case of relatively long paths would thus be preferable and a logarithmic trend seems a good compromise.

5.2. Evaluation of results

The simulation results obtained using the above set of parameters for the three emission points are reported in Figs. 11–13.

A relevant issue is now to assess the degree of matching between the simulated lava flow and the corresponding historical coverage. As we already

(a)	Constant function:	$F(c_i) = \text{constant}$,	$i = 0, \ldots, \text{Max}L$.
(b)	Linear function:	$F_{\text{lin}}(c_i) = (\text{Max}H/\text{Max}L)*i$,	$i = 0, \ldots, \text{Max}L$.

The lava flow height increases linearly with the length of the path

(c)   Logarithmic function: $F_{\log}(c_i) = \text{Max}H*\log_{\text{Max}L}(i+1)$ $i = 0, \ldots, \text{Max}L-1$.

The lava flow height increases in a logarithmic way with respect to the length (i.e. number of cells) of the path.
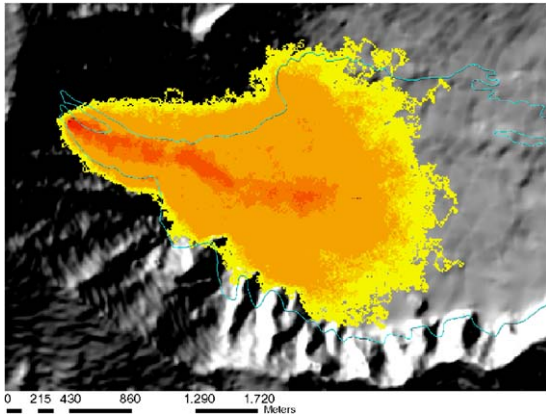
Fig. 5. Constant lava flow height, 500 cells. Blue line indicates boundary of past lava flow while ramp of colours from yellow to red ranks values assigned to cells.
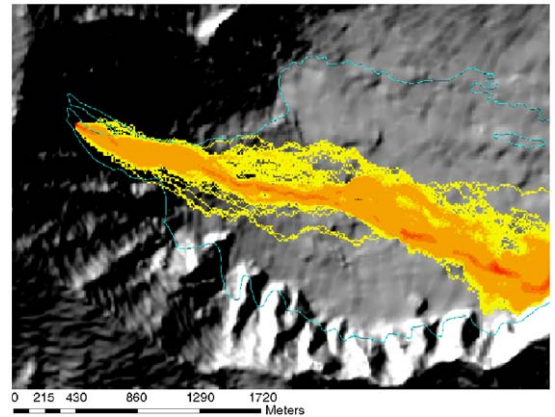

Fig. 8. (Linear) Variable lava flow height, 5000 cells. Blue line indicates boundary of past lava flow while ramp of colours from yellow to red ranks values assigned to cells.
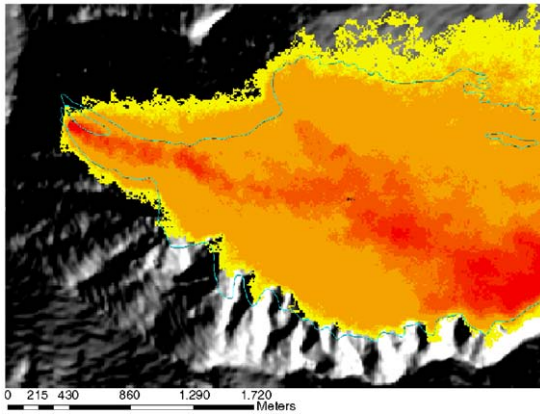

Fig. 6. Constant lava flow height, 5000 cells. Blue line indicates boundary of past lava flows while ramp of colours from yellow to red ranks values assigned to cells.
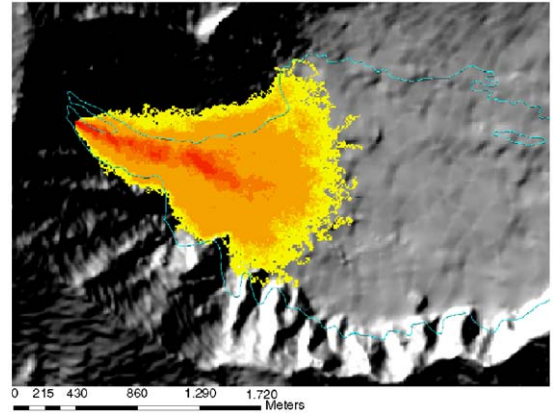

Fig. 9. (Log) Variable lava flow height, 500 cells. Blue line indicates boundary of past lava flow while ramp of colours from yellow to red ranks values assigned to cells.
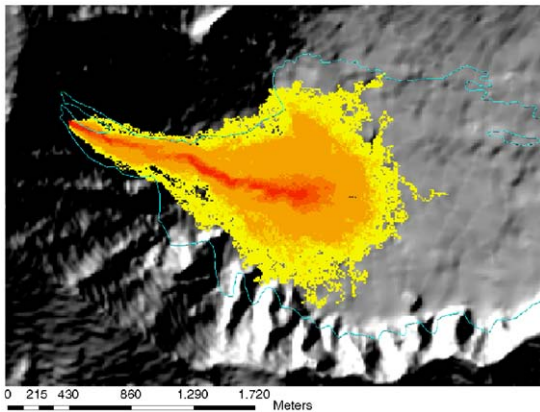

Fig. 7. (Linear) Variable lava flow height, 500 cells. Blue line indicates boundary of past lava flow while ramp of colours from yellow to red ranks values assigned to cells.
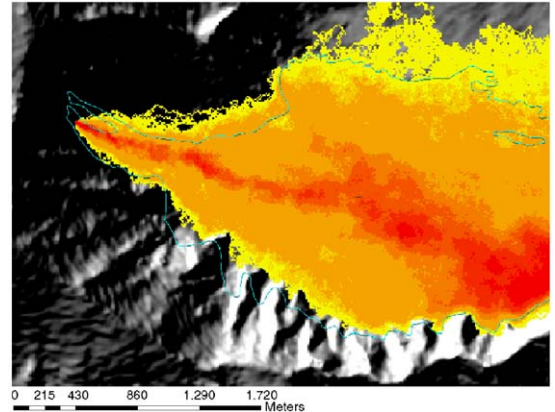

Fig. 10. (Log) Variable lava flow height, 5000 cells. Blue line indicates boundary of past lava flow while ramp of colours from yellow to red ranks values assigned to cells.
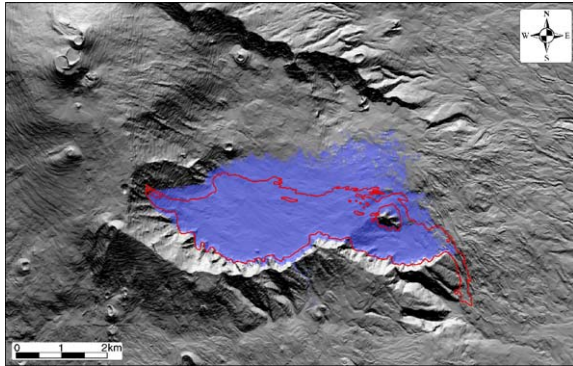
Fig. 11. Eruption of 1991. Red line indicates boundary of past lava flow while blue area shows simulation results.
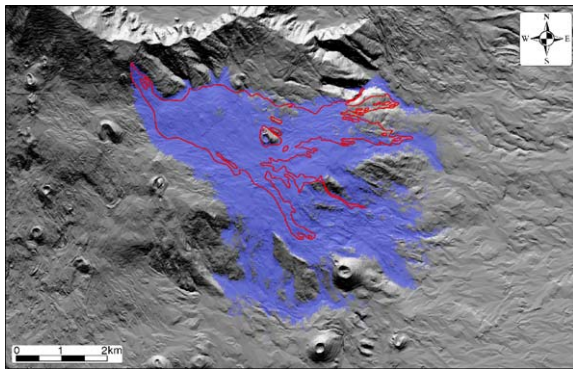

Fig. 12. Eruption of 1792. Red line indicates boundary of past lava flow while blue area shows simulation results.
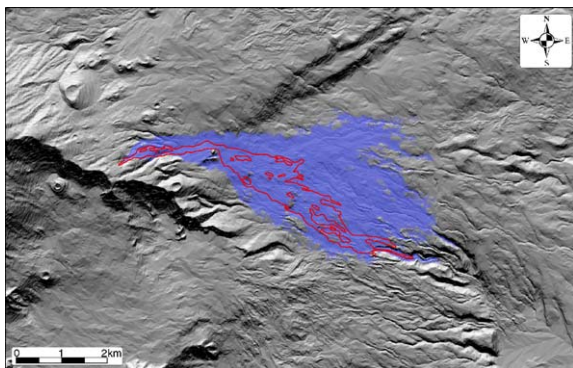

Fig. 13. Eruption of 1971. Red line indicates boundary of past lava flow while blue area shows simulation results.

metric for quantifying the degree of fit, i.e. how close the shapes of the lava flows are.

When looking at the previous figures (namely, Figs. 11–13) we can notice that the best matching has been obtained for the simulation of the eruption of 1991. Conversely, in the other two cases the matching is not equally precise as the simulated lava flow extends approximately 1500 m beyond the historical boundaries.

The mismatch however needs to be carefully evaluated. An important factor to be taken into account is that the simulations may be affected by the date the DEM goes back to. In this case, the data on which the DEM is based go back to 1986. This fact implies that the simulation of 1991 eruption is based on a reliable topography whereas those generated for the eruptions of 1792 and 1971 are based on a topography which is different from that existing at the date of eruptions. Ultimately the temporal misalignment of data generates a noise that may affect the simulation in an unpredictable way.

However, we can also notice that in all the three cases the shapes of the simulated lava flow cover nearly all the past coverage. That is important because it means that the simulated flow field anyway contains the actual lava flow. Another factor to consider is that a discrepancy of 1500–2000 m between the simulated lava flow and the historical boundaries can be tolerated because the purpose of the simulations is not that of predicting the path of a single lava flow but rather shaping the hazard zones for the hazard map of the volcano. Moreover it is important to remark that these simulations are generated using minimal information about the eruptions not including for example any data about effusion rate, eruption duration and the type of lava flow field. Ultimately the model is able to work although some volcanic parameters are not known and that is extremely important for the development of the hazard map.

With an accurate parameter tuning (Iterations, Max$H$, Max$L$ and F), the ELFM model can yield good results for open channel aa lava flows (1971 eruption), tube fed pahoehoe lava flows (1792) and aa with tube lava flows (1991–1993). The input parameters (Iterations, Max$H$, Max$L$ and F) approximate the behaviour of different lava flow fields of Mt. Etna (Kilburn and Lopez, 1988; Hon et al., 1994); thus, it can yield to valuable outcome, taking into account that it was designed to provide probabilistic medium-long term hazard assessment and not real time forecasting.

mentioned, if the simulated lava flow covered the area invaded by the historical lava flow fields then the matching would be satisfactory. In such a case, it is likely that a simulation will also cover the actual extent of the future lava flows. It should be noticed, however, that at the moment we do not use any
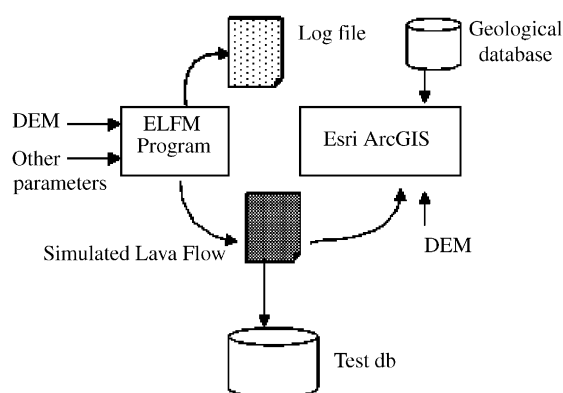
Fig. 14. System architecture.

Table 2
Computational time of algorithm

Iteration	Time
500	2′ 13″
1000	4′ 19″
2500	10′ 37″
5000	22′ 24″

6. System architecture

We conclude the paper by presenting the architectural framework that has been developed for supporting the implementation and validation of the simulation model (Fig. 14). The core of the system is the simulation software developed as a stand alone program (ELFM program). It has been written in C++ and runs on a standard configured PC (CPU: 2,6 GHz, Main Memory: 512 MB, Disk: 40 GB). Concerning the performance of the program, the computational time increases linearly with the number of iterations. In Table 2 we report the computation time for different number of iterations, assuming a fixed length for the lava flow.

The output of the program that is, the simulated lava flow, is represented in a proprietary file format that can be visualized using Esri ArcGIS. The architecture includes, however, all the modules needed to support the development of the model, specifically the geological database and a test database keeping track of the tests. The test database is of primary importance because the validation of the model is a time consuming activity producing a wealth of output data that need to be organized. A set of metadata is thus generated for the simulated lava flows including the parameter values and screenshots of the results. The test database is also

important for the maintenance and update of the hazard map.

7. Development of the hazard map for Mt. Etna: next steps

The proposed model represents the core component of a comprehensive methodology for the development of the hazard map for Mount Etna, currently under investigation. In particular, the methodology is centred on four major steps. The first aims at identifying possible emission regions, which are areas homogeneous with respect to lava flows behaviour as well the probability of an eruptive event. A preliminary zonation of the Eastern flank of Mount Etna is presented in Groppelli and Norini (2005). The purpose of the second step is to estimate a set of reference values for the parameters of the simulation model based on the knowledge of past eruptions in each emission area. Next, the simulation program is used to determine for each emission region the area that can be invaded by lava flows originated from sample points located in that region. The fourth and final step is to assign the probability of an eruptive event to each emission region and consequently to the lava invasion associated to such area.

8. Concluding remarks

The overall goal of the project is to define a methodology for the development of the hazard map of Mount Etna. The issue is challenging because, in spite of the fact that Mount Etna is one of the most active volcanoes in the world, the only hazard map that has been produced goes back to twenty years ago. The approach we have presented advances the current practices in that it aims at integrating conventional methods based on the analysis of past activity data with a stochastic model for lava flow simulation. In particular, we have integrated a high quality geological and stratigraphical database, managed through a GIS with a probabilistic simulation model of lava flows. The results can be summarized as follows:

(1) We have used at various steps a GIS because it is the best tool to evaluate volcanic hazard. In fact, this procedure can directly and immediately support semiautomatic or automatic data processing and can assure a better objective evaluation of hazard parameters;

(2) We have adopted a quantitative processing for the volcanic hazard assessment, starting from the geological data in order to assign each point of the region the probability that will be invaded by the lava flow, using a simulation model;

(3) We have started from a detailed geological map of the eastern flank of Mount Etna, using only the Holocene data, where the geological map and the related geological data base consist of more than 130 lava flows stored in a GIS;

(4) We have developed new software in C++ to improve the Felpeto's model used in the Canary Islands (Araña et al., 2000; Felpeto et al., 2001). Starting from the stochastic model of Felpeto, we have improved some functions, in particular, we modify the algorithm to solve the flow loop problem with a dynamic DEM, so we can establish the length and the height of each lava flow simulation; moreover we can change the lava flow height during the flow path based on the distance with different function (linear or logarithmic);

(5) We have made extensive tests to validate our simulation software; we have chosen three real and recent lava flows (1792, 1971, 1991–1993) on the eastern flank of Mount Etna and we have simulated lava flow paths from the same emission point.

The results we have achieved so far are encouraging. Therefore the simulation model will be used in the next steps of the project.

We plan to extend the current work by addressing two open major issues:

- The first issue concerns completing the quantitative-driven hazard-zoning of Mount Etna.
- The second is related more to the technological aspects of the project and concerns the development of a flexible and extensible software platform supporting all phases of the methodology for the development of the volcanic hazard map.

An open issue is whether the simulation model can be generalized for application to similar volcanoes. If it were so, it would represent a valuable tool for the estimation of the lava flow volcanic hazard.

Appendix. pseudo-code of core part of simulation algorithm

```
INPUT PARAMETERS
G: reference grid of N*M cells
Dem: matrix of altitude value
Ep: emission point
MaxL: max length of the path
MaxH: max height of the lava flow
F: variation of lava flow height
Iterations: number of paths

OUTPUT PARAMETERS
Flow: matrix of probability values

LOCAL VARIABLES
Heigh: matrix of lava flow heights.
Path: matrix describing the single path.
Cc: current cell. The cell is a data structure defined by the coordinates: Cc.x is the row, Cc.y is the column.
```

Cc is initialized to the emission point
Dc: destination cell.
Length: length of the current path initialised to 1
Delta: lava flow height increase

BODY
// the cycle computing the sequence of paths
FOR I = 1 TO Iterations REPEAT
  {
// the cells of the Path mat are set to 0 while the cell corresponding to the emission point Ep is set to 1
InizializePath (Path, Ep);

Terminate ← FALSE

///
// loop for path computation
///

  WHILE NOT Terminate DO
   {
//check the terminating conditions

   IF (Is_onTheBorder(Dem, Cc) // if the current cell is on the border of the Dem
    OR
    Length = MaxL)   // if the path has reached the maximum length
   THEN
    Terminate = TRUE
   ELSE
    {
    Cc ← ComputeDc(Dem, Heigh, Cc); // computation of the destination cell and assignment to the
    current cell
    Length ← Length + 1;   // increase of the path length
    delta ← F(Length);   // computation of the variable δ
    Path(Cc.x, Cc.y) ← 1   // updating of the Path sequence
    Heigh(Cc.x, Cc.y) ← Heigh(Cc.x, Cc.y) + delta; // the thickness of the lava flow at the current cell is
    increased of δ
    }
  }END DO
//
SumPath (Flow, Path) // the computed path is added to the resulting lava flow grid
}END FOR

ComputePercentage(Flow, Iterations); // final computation of the probabilities for the cells of being
invaded by lava

}END MAIN
// Here follows the definition of the main subroutine, for computing the destination cell

FUNCTION ComputeDc(Dem AS FLOAT(,), Height AS FLOAT(,), Cc AS CELL) AS CELL
{
  S_0 ← 0;
  // Function call that assigns the 8 surrounding cells of Cc to the array cell()

```
ComputeSurrCells(Cell(), Cc, Dem);
FOR i = 1 TO 8 DO
{
// Assignment of probability of the i-th cell, where ComputeDiff() gives the difference in height between
the cell where the flow is (Cc) and each of the neighboring ones
    P_i ← ComputeDiff(Cell(i), Cc, DEM, Height) /Sum_{j = 1 TO 8}(ComputeDiff(Cell(j), Cc, DEM, Height))
    ;
    S_i ← Sum_{k = 1 TO i} (P_k);
}END FOR
t ← RAND();                    //generation of a random number between 0 and 1
Terminate ← FALSE;
i ← 1;
WHILE NOT Terminate DO
{
    IF (S_{i−1} < = t < S_i) THEN
    {
        RETURN Cell(i);   // returns the i-th surrounding cell of Cc
        Terminate ← TRUE;
    }
    i ← i + 1;
}END DO
}END FUNCTION
```

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