CELLULAR AUTOMATA SIMULATION OF LAVA FLOWS
Applications to Civil Defense and Land Use Planning with a Cellular Automata based Methodology

Rocco Rongo[1], Valeria Lupiano[1], Maria Vittoria Avolio[2],
Donato D'Ambrosio[2], William Spataro[2] and Giuseppe A. Trunfio[3]
[1]*Department of Earth Sciences, University of Calabria, Via Pietro Bucci, I-87036 Rende, Italy*
[2]*Department of Mathematics, University of Calabria, Via Pietro Bucci, I-87036 Rende, Italy*
[3]*Department of Architecture, Planning and Design, University of Sassari, Piazza Duomo 6, 07041, Alghero, Italy*

Keywords: Lava flows simulation, Cellular automata, Hazard maps, Land use planning, Mt Etna.

Abstract: A large number of people live either on or in the surrounding areas of hundreds of worldwide active volcanoes. For this reason, the individuation of those areas that are more likely to be affected by new eruptive events is of fundamental importance for diminishing possible consequences in terms of loss of human lives and/or material properties. We here illustrate a methodology for defining flexible high-detailed lava invasion hazard maps which is based on a efficient Cellular Automata computational model for simulating lava flows on present topographic data and on High Performance Parallel Computing for increasing computational efficiency. We also show the application of the methodology to the entire area surrounding Mt Etna (Italy), Europe's most active volcano, showing its suitability for land use planning and civil defence applications. Furthermore, specific applications to inhabited areas of the volcano are also shown, which demonstrate the methodology's applicability in this field.

1 INTRODUCTION

Despite being the most active volcano in Europe, Mt Etna (South Italy) is home to approximately one million people (Behncke and Neri, 2003). Still, the majority of the events occurred in the last four centuries report damage to human properties in numerous towns on the volcano flanks. In last decades, the susceptibility of the Etnean area to lava invasion has increased due to continued urbanization (Dibben, 2008), with the consequence that new eruptions may involve even greater risks. Different countermeasures based on embankments or channels were adopted in recent crises to stop or deflect lava (Barberi et al., 1993) (Barberi et al., 2003). However, such kinds of interventions are generally performed while the eruption is in progress, with the consequence of both not guarantying their effectiveness, besides inevitably putting into danger the safety of involved persons. One response to such challenges is the numerical simulation of lava flows (Ishihara et al., 1990), (DelNegro et al., 2008), (Avolio et al., 2006), for the purpose of individuating affected areas in advance. As a matter of fact, in 2001 the path of the eruption that threatened the town of Nicolosi on Mt Etna was correctly predicted by means of a lava flows simulation model (Crisci et al., 2004), providing at that time useful information to local Civil Defense authorities. However, in order to be efficiently and correctly applied, the above approaches require an a priori knowledge of the degree of exposure of the volcano surrounding areas, to allow both the realization of preventive countermeasures, and a more rational land use planning. Based on an improved version of the SCIARA cellular automata lava flow model (Crisci et al., 2004), we here illustrate a methodology for the definition of flexible high-resolution lava invasion hazard maps, and show results related to Mt Etna. Furthermore, we show specific applications that can be useful for civil defense purposes and land use planning.

2 THE SCIARA MODEL

In order to be applied for land use planning and civil defense purposes in volcanic regions, a computational model for simulating lava flows should be

Rongo R., Lupiano V., Avolio M., D'Ambrosio D., Spataro W. and Trunfio G..
CELLULAR AUTOMATA SIMULATION OF LAVA FLOWS - Applications to Civil Defense and Land Use Planning with a Cellular Automata based Methodology.
DOI: 10.5220/0003575900370044
In *Proceedings of 1st International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2011), pages 37-44
ISBN: 978-989-8425-78-2

well calibrated and validated against test cases to assess its reliability, cf. e.g. (DelNegro et al., 2008) (Rongo et al., 2008) (Vicari et al., 2007). Another desirable characteristic should be the model's efficiency since, depending on the extent of the considered area, a great number of simulations could be required (D'Ambrosio et al., 2006), (Crisci et al., 2010). A first computational model of basaltic lava flows, based on the Cellular Automata computational paradigm and, specifically, on the Macroscopic Cellular Automata approach for the modeling of spatially extended dynamical systems, was proposed in (Crisci et al., 1982) called SCIARA. In the following years, the SCIARA family of lava flows simulation models have been improved and applied with success to the simulation of different Etnean cases of study, e.g. (Crisci et al., 2004) (Rongo et al., 2008).

Cellular Automata (CA) (Neumann, 1966) were introduced in 1947 by the John von Neumann in his attempt to understand and formalise the underling mechanisms that regulate the auto-reproduction of living beings. After the publication of his studies, Cellular Automata quickly came to the attention of the Scientific Community both as powerful parallel computational models and as convenient tools for modelling and simulating several types of complex physical phenomena (Chorpard and Droz, 1998).

Classical Cellular Automata can be viewed as an n-dimensional space, R, subdivided in cells of uniforms shape and size. Each cell embeds an identical finite automaton (fa), whose state accounts for the temporary features of the cell; Q is the finite set of states. The fa input is given by the states of a set of neighbouring cells, including the central cell itself. The neighbourhood conditions are determined by a geometrical pattern, X, which is invariant in time and space. The fa have an identical state transition function $\tau : Q^{\sharp X} \rightarrow Q$, where $\sharp X$ is the cardinality of the set of neighbouring cells, which is simultaneously applied to each cell. At step $t = 0$, fa are in arbitrary states and the CA evolves by changing the state of all fa simultaneously at discrete times, according to τ.

Macroscopic Cellular Automata (MCA) (DiGregorio and Serra, 1999) introduce some extensions to the classical CA formal definition. In particular, the Q of state of the cell is decomposed in r substates, Q_1, Q_2,..., Q_r, each one representing a particular feature of the phenomenon to be modelled (e.g. for lava flow models, cell temperature, lava content, outflows, etc). The overall state of the cell is thus obtained as the Cartesian product of the considered substates: $Q = Q_1 \times Q_2 \times ... \times Q_r$. A set of parameters, $P = \{p_1, p_2, ..., p_p\}$, is furthermore considered, which allow to "tune"the model for reproducing different dynamical behaviours of the phenomenon of interest (e.g. for lava flow models, the Stephan-Boltzmann constant, lava density, lava soldification temperature, etc). As the set of state is split in substates, also the state transition function τ is split in elementary processes, $\tau_1, \tau_2, ..., \tau_s$, each one describing a particular aspect that rules the dynamic of the considered phenomenon. Eventually, $G \subset R$ is a subset of the cellular space that is subject to *external influences* (e.g. for lava flow models, the crater cells), specified by the supplementary function γ. External influences are introduced in order to model features which are not easy to be described in terms of local interactions.

In the MCA approach, by opportunely discretizing the surface on which the phenomenon evolves, the dynamics of the system can be described in terms of flows of some quantity from one cell to the neighbouring ones. Moreover, as the cell dimension is a constant value throughout the cellular space, it is possible to consider characteristics of the cell (i.e. substates), typically expressed in terms of volume (e.g. lava volume), in terms of thickness. This simple assumption permits to adopt a straightforward but efficacious strategy that computes outflows from the central cell to the neighbouring ones in order to minimize the non-equilibrium conditions.

Still, owing to their intrinsic parallelism, both CA and MCA models implementation on parallel computers is straightforward, and the simulation duration can be reduced almost proportionally to the number of available processors (D'Ambrosio and Spataro, 2007).

In this work, the latest release of the SCIARA Cellular Automata model for simulating lava flows was adopted. Specifically, a Bingham-like rheology has been introduced for the first time as part of the Minimization Algorithm of the Differences (DiGregorio and Serra, 1999), which is applied for computing lava outflows from the generic cell towards its neighbors. Besides, the hexagonal cellular space adopted in the previous releases (Crisci et al., 2004) of the model for mitigating the anisotropic flow direction problem has been replaced by a square one, nevertheless by producing an even better solution for the anisotropic effect. The model has been calibrated by considering three important real cases of studies, the 1981, 2001 and 2006 lava flows at Mt Etna (Italy), and on ideal surfaces in order to evaluate the magnitude of anisotropic effects. Even if major details of this advanced model can be found in (Spataro et al., 2010), we briefly outline it's main specifications.

In formal terms, the SCIARA MCA model is defined as:

$$SCIARA = < R, L, X, Q, P, \tau, \gamma > \quad (1)$$

where:

- R is the set of square cells covering the bi-dimensional finite region where the phenomenon evolves;
- $L \subset R$ specifies the lava source cells (i.e. craters);
- $X = \{(0,0),(0,1),(-1,0),(1,0),(0,-1),(-1,1),(-1,-1),(1,-1),(1,1)\}$ identifies the pattern of cells (Moore neighbourhood) that influence the cell state change, referred to cells by indexes 0 (for the central cell) through 8;
- $Q = Q_z \times Q_h \times Q_T \times Q_f^8$ is the finite set of states, considered as Cartesian product of "substates". Their meanings are: cell elevation a.s.l. (above sea level), cell lava thickness, cell lava temperature, and lava thickness outflows (from the central cell toward the eight adjacent cells), respectively;
- $P = \{w, t, T_{sol}, T_{vent}, r_{Tsol}, r_{Tvent}, hc_{Tsol}, hc_{Tvent}, \delta, \rho, \varepsilon, \sigma, c_\nu\}$ is the finite set of parameters (invariant in time and space) which affect the transition function (please refer to (Spataro et al., 2010) for their specifications);
- $\tau : Q^9 \to Q$ is the cell deterministic transition function, applied to each cell at each time step, which describes the dynamics of lava flows, such as cooling, solidification and lava outflows from the central cell towards neighbouring ones;
- $\gamma : Q_h \times \mathbb{N} \to Q_h$ specifies the emitted lava thickness, h, from the source cells at each step $k \in \mathbb{N}$ ($\mathbb{N}$ is the set of natural numbers).

As stated before, the new SCIARA model introduces a rheology inspired to the Bingham model and therefore the concepts of critical height and viscosity are explicitly considered (Park and Iversen, 1984), (Dragoni et al., 1986). In particular, lava can flow out from a cell towards its neighbours if and only if its thickness overcomes a critical value (i.e. the critical height), so that the basal stress exceeds the yield strength. Moreover, viscosity is accounted in terms of flow relaxation rate, r, a the parameter of the distribution algorithm that influences the amount of lava that actually leaves the cell, according to a power law of the kind:

$$\log r = a + bT \qquad (2)$$

where T is the lava temperature and a and b coefficients determined by solving the system:

$$\begin{cases} \log r_{Tsol} = a + bT_{sol} \\ \log r_{Tvent} = a + bT_{vent} \end{cases}$$

where T_{sol} and T_{vent} are the lava temperature at solidification and at the vents, respectively. Similarly, the critical height, hc, mainly depends on lava temperature according to a power law of the kind:

$$\log hc = c + dT \qquad (3)$$

whose coefficients c and d are obtained by solving the system:

$$\begin{cases} \log hc_{Tsol} = c + dT_{sol} \\ \log hc_{Tvent} = c + dT_{vent} \end{cases}$$

It is known that, in general, deterministic CA for the simulation of macroscopic fluids present a strong dependence on the cell geometry and directions of the cellular space. In order to solve the problem, different solutions have been proposed in literature, such as the adoption of hexagonal cells (Crisci et al., 2004), (Avolio et al., 1998), (D'Ambrosio et al., 2003) or Monte Carlo approaches (Miyamoto and Sasaki, 1997), (Vicari et al., 2007). The first solution, however, does not perfectly solve the problem on ideal surfaces, while the second one has the disadvantage of giving rise to non-deterministic simulation models. In order to solve the anisotropic problem, which is typical of deterministic Cellular Automata models for fluids on ideal surfaces, a fictitious topographic alteration along diagonal cells is considered with respect to those "individuated" by the DEM (Digital Elevation Model). As a matter of fact, in a standard situation of non-altered heights, cells along diagonals result in a lower elevation with respect to the remaining ones (which belong to the von Neumann neighborhood), even in case of constant slope. This is due since the distance between the central cell and diagonal neighbors is greater than of the distance between the central cell and orthogonal adjacent cells (cf. Figure 1). This introduces a side effect in the distribution algorithm, which operates on the basis of height differences. If the algorithm perceives a greater difference along diagonals, it will erroneously privilege them by producing greater outflows. In order to solve this problem, we consider the height of diagonal neighbors taken at the intersection between the diagonal line and the circle with radius equal to the cell side and centered in the central cell, so that the distance with respect to the centre of the central cell is constant for each cell of the Moore neighbourhood (Figure 1). Under the commonly assumed hypothesis of inclined plane between adjacent cells (Vicari et al., 2007), this solution permits to have constant differences in level in correspondence of constant slopes, and the distribution algorithm can work "properly". Refer to (Spataro et al., 2010) for other specifications on this issue.

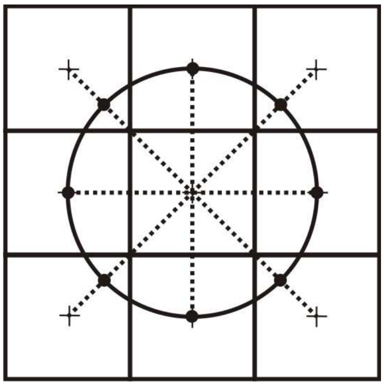

Figure 1: Reference schema for cells altitude determination in the Moore neighbourhood. Altitudes of cells belonging to the von Neumann neighbourhood correspond to normal DEM values, while those along diagonals are taken at the intersection between the diagonal line and the circle with radius equal to the cell side, so that the distance with respect to the centre of the central cell is constant for each adjacent neighbour.

3 A METHODOLOGY FOR CREATING HAZARD MAPS

While a reliable simulation model is certainly a valid instrument for analyzing volcanic risk in a certain area by simulating possible *single* episodes with different vent locations, e.g. (Crisci et al., 1999), the methodology for defining high detailed hazard maps here presented is based on the application of the SCIARA lava flows computational model for simulating an *elevated* number of new events on topographic data. In particular, the methodology requires the analysis of the past behavior of the volcano, for the purpose of classifying the events that historically interested the region. In such a way, a meaningful database of plausible simulated lava flows can be obtained, by characterizing the study area both in terms of areal coverage, and lava flows typologies. Once the simulation database has been completed (i.e., an adequate, usually elevated, number of simulations have been carried out), data is processed by considering a proper criterion of evaluation. A first solution could simply consist in considering lava flows overlapping, by assigning a greater hazard to those sites interested by a higher number of simulations. However, a similar choice could be misleading. In fact, depending on their particular traits (e.g., location of the main crater, duration and amount of emitted lava, or effusion rate trend), different events can occur with different probabilities, which should be taken into account in evaluating the actual contribution of performed simulations with respect to the definition of the overall hazard of the study area. In most cases, such probabilities can be properly inferred from the statistical analysis of past eruptions, allowing for the definition of a more refined evaluation criterion. Accordingly, in spite of a simple hitting frequency, a measure of lava invasion hazard can be obtained in probabilistic terms. In the following, we show how such approach was applied to Mt Etna.

3.1 Application of the Methodology to the Mt. Etna Volcano Area

By adopting a procedure well described in (Crisci et al., 2010) and (Avolio et al., 2010), which referred to the Eastern sector of Mt. Etna and which was applied by employing a previous version of the SCIARA CA model, we here show the application to the entire area of the volcano using the new SCIARA model described in Section 2. Firstly, based on documented past behavior of the volcano, the probability of new vents forming was determined, resulting in a characterization (thus, a Probability Density Function - PDF - map) of the study region into areas (Figure 2), that represent different probabilities of new vents opening (Cappello et al., 2011), assessed by employing a Poisson distribution which considers a spatial density and a temporal component. The spatial probability density function was estimated through a Gaussian kernel by considering the main volcanic structures at Mt Etna, while the temporal rate was evaluated by using an approach based on the "repose-time method" (Ho et al., 1991).

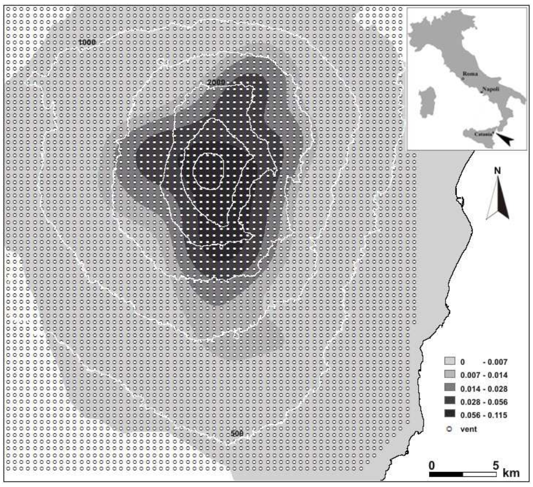

Figure 2: The characterization of new vents forming of the study region on the basis of historical data (see text), representing different probabilities of activation, considered in this work, together with the grid of 4290 hypothetical vents defined as the source for the simulations to be carried.

Subsequently, all flank eruptions of Etna since

1600 AD were classified according to duration and lava volume (Crisci et al., 2010) and a representative effusion rate trend taken into account in order to characterize lava temporal distribution for the considered representative eruptions, basically reflecting the effusive mean behavior of Etnean lava flows. In fact, with the exception of few isolated cases, a typical effusive behavior was strongly evidenced by the analysis of the volcano past activity (Behncke et al., 2005). As a consequence, it is not a hasty judgment to suppose that such behavior will not dramatically change in the near future and thus that the SCIARA lava flows simulation model, calibrated and validated on a set of effusive eruptions, be adequate for simulating new events on Mt Etna. An overall probability of occurrence, p_e, was thus defined for each scenario, by considering the product of the individual probabilities of its main parameters:

$$p_e = p_s \cdot p_c \cdot p_t \quad (4)$$

where p_s denotes the probability of eruption from a given location (i.e., based on the PDF map), p_c the probability related to the event's membership class (i.e., emitted lava and duration), and p_t the probability related to its effusion rate trend.

Once representative lava flows were devised as above, a set of simulations were planned to be executed in the study area by means of the SCIARA lava flows simulation model. At this purpose, a grid composed by 4290 craters, equally spaced by 500m, was defined on the considered as a covering for Mt Etna, as shown in Figure 2. This choice allowed to both adequately and uniformly cover the study area, besides considering a relatively small number of craters. Specifically, a subset of event classes which define 6 different effusion rates probabilities, derived from historical events considered in (Crisci et al., 2010), were taken into account for each crater, thus resulting in a total of 25740 different simulations to be carried out. Owing to the elevated number of SCIARA simulations to be carried out, thanks to the adoption of Parallel Computing each scenario was simulated for each of the vents of the grid. Simulations were performed on an 80-node Apple Xserve Xeon-based cluster and were performed in ca. 10 days.

Lava flow hazard was then punctually evaluated by considering the contributions of all the simulations which affected a generic cell in terms of their probability of occurrence. Formally, if a given DEM cell (and thus, a CA cell) of co-ordinates (x,y) is affected by $n_{x,y} \leq N$ simulations, being N the overall number of performed simulations, its hazard $h_{x,y}$ can be defined as the sum of the probabilities of occurrence of involved lava flows, $p_e(i)$ (i=1, 2, ..., $n_{x,y}$):

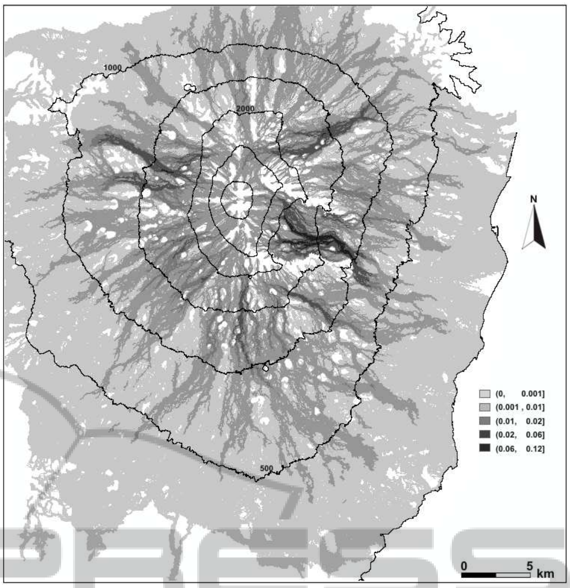

Figure 3: Hazard map of the study area based on the 25740 simulations. As a compromise between map readability and accuracy, 5 classes are reported (grey colouring), in increasing order of susceptibility (probability of lava invasion).

$$h_{x,y} = \sum_{i=1}^{n_{x,y}} p_e(i) \quad (5)$$

The obtained lava flow hazard map resulting from these simulations and the application of equation 5 is presented in Figure 3, and represents the probability that future eruptions will affect the entire Etnean area.

Importantly, the methodology for the compilation of lava flows invasion hazard maps here proposed provides for, as integrant part, a process for the verification of results. A validation procedure was thus contemplated for the produced hazard map, consisting in a technique which produces statistical indicators on which one can quantify the reliability of the results and, therefore, assess whether the final product can be confidently used for Civil Protection, for example, for setting in safety particularly vulnerable areas, and for Land Use Planning. Refer to (Crisci et al., 2010) for major details on the methodology validation process.

4 APPLICATIONS FOR CIVIL DEFENSE AND LAND USE PLANNING

Apart leading for the definition of general hazard maps, as the one reported in Figure 3, the methodology permits further Civil Defense oriented applications. For this purpose, the calibrated and validated SCIARA simulation model has been integrated

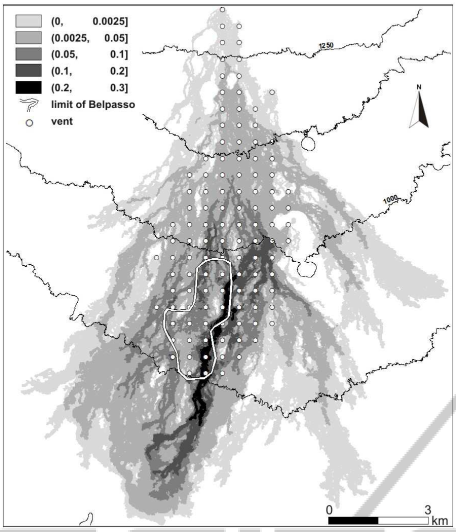

Figure 4: Map showing vents, belonging to the simulation grid of Fig. 2, which can produce eruptions capable of affecting the urban area of the town of Belpasso, together with the resulting susceptibility scenario, allowing to immediately assess the threat posed by an eruption exclusively on the basis of its source location.

in a GIS (Geographic Information System) application that permits to take also into account the effects of "virtual" embankments, channels, barriers, etc. In particular, the availability of a large number of lava flows of different eruption types, magnitudes and locations simulated for this study allows the instantaneous extraction of various scenarios. This is especially relevant once premonitory signs indicate the possible site of imminent eruptions, and thus permitting to consider hazard circumscribed to a smaller area.

A first Civil Defense oriented application regards the possibility to identify all source areas of lava flows that are capable of affecting a given area of interest, such as a town or a major infrastructure. In this case, this application is rapidly accomplished by querying the simulation database, by selecting the lava flows that affect the area of interest and by circumscribing their sources. For this application we have chosen the towns of Belpasso and Zafferana Etnea, two important historical and cultural sites, with many administrative buildings and tourist facilities. Figure 4 and Figure 5 show vents which can originate eruptions capable of affecting the urban areas of Belpasso and Zafferana Etnea, respectively, together with the resulting hazard scenario, allowing to immediately assess the threat posed by an eruption exclusively on the basis of its source location.

Etnean eruptions can even comprise complex events, which for Etna are fairly typical, such as lava

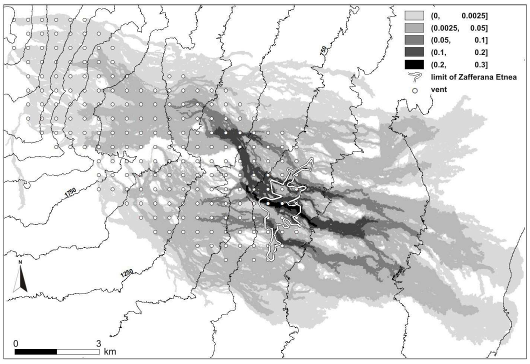

Figure 5: A second example of application of hazard zonation referred to the town of Zafferana Etnea. Even in this case, the map shows vents which can produce eruptions capable of affecting the urban area of the town. As before, an elevated risk is present for the center of the inhabited area

emission from an extensive system of eruptive fissures propagating downslope over a length of several kilometers. We have performed an analysis for such an eruption on the east-northeast flank of Etna, not far from the 1928 eruption site, with lava emission from a fissure system about 7km long. The eruptive system was approximated by a subset of vents of the simulation grid and all lava flows originated from them selected from the simulation database (without needing to perform new simulations). For this application, the resulting map is shown in Figure 6. The same figure refers also to a further application regarding temporal hazard mapping, by evidencing the evolution of the involved area in time. This application could be of fundamental importance for assessing, from a temporal point of view, how hazard of a specific area evolves in time (e.g. day by day), so that more specific countermeasures can be considered by responsible authorities.

Specifically, Figure 6 also shows the result relative to 1, 3, 6 and 9 days respectively, of the invaded areas, with relative probability values of occurrence, in the case of the activation of the considered fissure system. This application regards a real-time assessment of lava invasion in confined areas, since the produced map indicates a temporal evolution of hazard, in terms of probability, which can be useful in case of an imminent/new event to Civil Protection to monitor, and eventually intervene, in areas with higher values of lava hazard, without having information on the event's duration and emission rate that take place.

Other examples of applications referred to risk mitigation can be considered for testing the impact of human intervention during an eruption, in order to assess the effect of possible human interventions with the aim for decreasing hazard in critical areas. For instance, it is possible to evaluate the effect, in terms

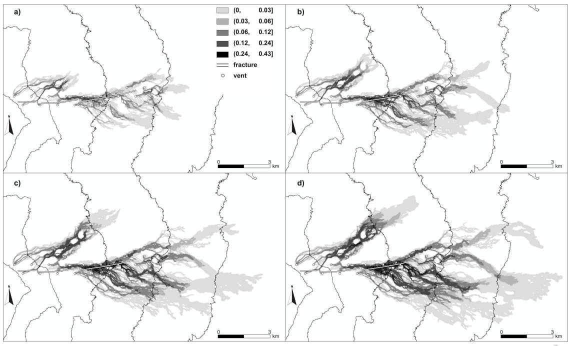

Figure 6: A hypothetical hazard scenario for a system of eruptive fissures propagating downslope over a length of 7 km on the east-northeast flank of Mount Etna. The figure refers to lava hazard of the area after 1, 3, 6 and 9 days (a, b, c, d), respectively. Note that the same scenarios can be considered as temporal scenario for the area.

of hazard decrease, of barriers or channels built to protect inhabited areas. Please refer to (Crisci et al., 2010) for specific examples regarding a case study performed for evaluating the impact of a barrier to protect the town of Nicolosi, a strategic town of the Etnean area.

5 CONCLUSIONS

We have presented an application of Cellular Automata for defining high-detailed hazard maps which can be fruitfully applied for land use planning and civil defense purposes. Based on the adoption of the latest release of the Macroscopic Cellular Automata model SCIARA for simulating lava flows, which considers a Bingham-like rheology, the methodology permits the creation of general lava flow hazard maps, which can be fundamental for land-use and civil defense planning in the long-term. Regarding the adopted new computational model, which is at the basis of the methodology, SCIARA re-introduces a square tessellation of the cellular space instead of the previously adopted hexagonal one, which was considered in the earlier versions to limit the effect of the anisotropic flow direction problem.

A novelty of the presented methodology, besides the possibility of assessing the efficiency of protective measures for inhabited areas and/or major infrastructures, is that the simulation data permits to produce general susceptibility maps in unprecedented detail, and contains each single scenario out of a total of over thousands of simulated cases. It is therefore no longer necessary to wait for the next eruption and know its eruptive parameters and location in order to run ad-hoc simulations, as has been the practice until now. Instead, virtually all possible eruption scenarios can be simulated a priori, from as dense a network of hypothetical vent locations as possible, and extracted in real time as soon as the need arises, as in the case of an imminent or incipient eruptions.

The methodology here described can therefore represent a substantial advance in the field of lava flow impact prediction and can also have immediate, far reaching implications both in land use and civil defense planning.

ACKNOWLEDGEMENTS

Authors thank Dr. B. Behncke and Dr. M. Neri from the INGV - Istituto Nazionale di Geofisica e Vulcanologia of Catania (Sicily, Italy), who provided topographic maps and the volcanological data. The authors are also grateful to Prof. G.M. Crisci and Prof. S. Di Gregorio for their precious comments and the common researches.

REFERENCES

Avolio, M., Crisci, G., S.DiGregorio, Rongo, R., Spataro, W., and D'Ambrosio, D. (2006). Pyroclastic flows modelling using cellular automata. *Comp. Geosc.*, 32:897–911.

Avolio, M., D'Ambrosio, D., DiGregorio, S., Lupiano, V., Rongo, R., and Spataro, W. (2010). Evaluating lava flow hazard at Mount Etna (Italy) by a cellular automata based methodology. *LNCS*, 6068:495–504.

Avolio, M., DiGregorio, S., Rongo, R., Sorriso-Valvo, M., and Spataro, W. (1998). Hexagonal cellular automata model for debris flow simulation. In *Proceedings of IAMG*, pages 183–188. Litografia Editrice, Naples.

Barberi, F., Brondi, F., Carapezza, M. L., Cavarra, L., and Murgia, C. (2003). Earthen barriers to control lava flows in the 2001 eruption of Mt. Etna. *J. Volcanol. Geotherm. Res.*, 123:231–243.

Barberi, F., Carapezza, M., Valenza, M., and Villari, L. (1993). The control of lava flow during the 1991-1992 eruption of Mt. Etna. *J. Volcanol. Geotherm. Res.*, 56:1–34.

Behncke, B. and Neri, M. (2003). Cycles and trends in the recent eruptive behaviour of Mount Etna (Italy). *Can. J. Earth Sci.*, 40:1405–1411.

Behncke, B., Neri, M., and Nagay, A. (2005). New data from a GIS-based study, kinematics and dynamics of lava flows. *Geol. Soc. Am. Spec. Pap.*, 396:189–208.

Cappello, A., Vicari, A., and DelNegro, C. (2011). A retrospective validation of lava flow hazard map at Etna volcano. *Spec. Issue of Annals of Geophy.*, *To Appear*.

Chorpard, B. and Droz, M. (1998). *Cellular Automata Modeling of Physical Systems*. Cambridge University Press, UK.

Crisci, G., Avolio, M., Behncke, B., D'Ambrosio, D., Di-Gregorio, S., Lupiano, V., Neri, M., Rongo, R., and Spataro, W. (2010). Predicting the impact of lava flows at Mount Etna. *J. Geophy. Res.*, 115(B0420):1–14.

Crisci, G., DiGregorio, S., Nicoletta, F., Rongo, R., and Spataro, W. (1999). Analysing lava risk for the etnean area: Simulation by cellular automata methods. *Natural Hazards*, 20:215–229.

Crisci, G., DiGregorio, S., and Ranieri, G. (1982). A cellular space model of basaltic lava flow. In *Proceedings International AMSE Conference Modelling & Simulation*.

Crisci, G., Rongo, R., DiGregorio, S., and Spataro, W. (2004). The simulation model SCIARA: The 1991 and 2001 lava flows at Mount Etna. *J. Volc. Geoth. Res.*, 132:253–267.

D'Ambrosio, D., DiGregorio, S., and Iovine, G. (2003). Simulating debris flows through a hexagonal cellular automata model: Sciddica S3-hex. *Nat. Haz. Ear. Sys. Scien.*, 3:545–559.

D'Ambrosio, D., Rongo, R., Spataro, W., Avolio, M., and Lupiano, V. (2006). Lava invasion susceptibility hazard mapping through cellular automata. *LNCS*, 4173:452–461.

D'Ambrosio, D. and Spataro, W. (2007). Parallel evolutionary modelling of geological processes. *Paral. Comp.*, 33(3):186–212.

DelNegro, C., Fortuna, L., Herault, A., and Vicari, A. (2008). Simulations of the 2004 lava flow at Etna volcano using the magflow cellular automata model. *Bull. Volcanol.*, 70:805–812.

Dibben, C. (2008). Leaving the city for the suburbs - the dominance of 'ordinary' decision making over volcanic risk perception in the production of volcanic risk on Mt Etna, Sicily. *J. Volcanol. Geotherm. Res.*, 172:288–299.

DiGregorio, S. and Serra, R. (1999). An empirical method for modelling and simulating some complex macroscopic phenomena by cellular automata. *Fut. Gen. Comp. Sys.*, 16:259–271.

Dragoni, M., Bonafede, M., and Boschi, E. (1986). Downslope flow models of a Bingham liquid: Implications for lava flows. *J. Volc. Geoth. Res.*, 30(3-4):305–325.

Ho, C., Smith, E., Feuerbach, D., and Naumann, T. (1991). Eruptive calculation for the Yucca Mountain site, USA: Statistical estimation of recurrence rates. *Bull. Volcanol.*, 54:50–56.

Ishihara, K., Iguchi, M., and Kamo, K. (1990). Numerical simulation of lava flows on some volcanoes in Japan. In *IAVCEI Proceedings in Volcanology*, pages 174–207. Springer, Berlin Heidelberg New York.

Miyamoto, H. and Sasaki, S. (1997). Simulating lava flows by an improved cellular automata method. *Comp. Geosci.*, 23:283–292.

Neumann, J. V. (1966). *Theory of self-reproducing automata*. Univ. Illinois Press, Urbana.

Park, S. and Iversen, J. (1984). Dynamics of lava flow: Thickness growth characteristics of steady 2-dimensional flow. *Geophys. Res. Lett.*, 11:641–644.

Rongo, R., Spataro, W., D'Ambrosio, D., Avolio, M., Trunfio, G., and DiGregorio, S. (2008). Lava flow hazard evaluation through cellular automata and genetic algorithms: An application to Mt Etna volcano. *Fund. Inform.*, 8:247–268.

Spataro, W., Avolio, M., Lupiano, V., Trunfio, G., Rocco, R., and D'Ambrosio, D. (2010). The latest release of the lava flows simulation model SCIARA: First application to Mt Etna (Italy) and solution of the anisotropic flow direction problem on an ideal surface. In *Proccedings of the International Conference on Computational Science. ICCS 2010*, volume 1, pages 17–26. Procedia Computer Science.

Vicari, A., Herault, A., DelNegro, C., Coltelli, M., Marsella, M., and Proietti, C. (2007). Modelling of the 2001 lava flow at Etna volcano by a cellular automata approach. *Environ. Model. Soft.*, 22:1465–1471.