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Automatic GIS-based system for volcanic hazard assessment

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Abstract

This paper presents an automatic system for the elaboration of volcanic hazard maps and scenarios. The methodology used for the generation of both maps is based on the use of numerical simulation of eruptive processes. The system has been developed in a Geographical Information System (GIS) framework, where models for the numerical simulation of different volcanic hazards have been integrated. The user can select in a toolbar one hazard and then decide whether to generate a scenario map (usually with a unique vent) or a hazard map (generally with a broader source area). Once the input parameters are selected, the system automatically generates the corresponding map. The system also incorporates a module to determine the spatial probability of vent opening, as this could be an important parameter for the computation of hazard maps. The tool has been designed in such a way that the inclusion of new numerical models and functionalities is rather easy. Each numerical model is programmed and implemented as an independent program that is launched from the system and, when it finishes the computation, returns the control to the GIS, where the results are shown. This structure allows that further analyses (specifically, risk analyses, that use as an input a hazard or a scenario map), could be also automated inside the system. Additional information, including tutorial and downloadable files can be found in www.gvb-csic.es.

Keywords: volcanic hazard; vent opening; scenario; numerical simulation models; GIS

1. Introduction

Assessment and management of volcanic risk are important scientific, economic, and political issues, especially in densely populated areas threatened by volcanoes. The best treatment of these aspects requires accurate assessment and mitigation programmes, the development of effective tools for prediction and management of crises and the promotion of sustainable development within such regions.

Evaluation of volcanic risk is extremely complex because it can involve different hazardous phenomena including pyroclastic and lava flows, fallout of ash and tephra, earthquakes, landslides or floods. This multiplicity of hazardous phenomena has strongly constrained the evaluation and management of volcanic risk, despite the fact that advances and improvements in this scientific discipline could be easily exported and applied to assessment of risk from almost all natural hazards. From a scientific point of view, considerable progress has been made during recent years through the development of Geographic Information Systems (GIS), as well as to the deployment of increasingly

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powerful computational models and capabilities, which have permitted the development of new vulnerability databases and the probabilistic risk assessment protocol.

Nevertheless, despite these crucial advances, the evaluation of volcanic risk still has an important drawback, which derives from the large degree of expertise and scientific background required to use scientific hazard assessments. This precludes a wider use of scientific and technical advances by potential end users outside the scientific community and slows the social benefits of such improvements. Additionally, hazard assessment implies many steps, usually computed with different tools. This fact can be the origin of many errors, both made by the different operators or due to the transfer between different systems. It also could make all the procedure a high time-consuming process, therefore reducing the available time for a quick response in the case of a volcanic unrest.

In this paper, we introduce a new and simple e-tool specifically designed to assess volcanic hazard in active regions. It consists on an automatic system developed in a GIS framework, which allows the user to elaborate volcanic hazard maps and eruption scenarios from the information of past eruptions and the geology of the area. The aim of our automatic system is to provide the necessary hazard assessment for risk mitigation programmes and territorial planning in a rapid and easy way and using commonly available computing facilities. All the examples presented in the paper correspond to the island of Tenerife (Canary Islands), on which the application of the new automatic system has been used to elaborate volcanic hazard maps.

2. Methodology for the elaboration of hazard maps and eruption scenarios

Hazard can be defined as the probability for a point being affected by a hazardous process during a considered time interval Δt. Many different approaches have been used for the generation of volcanic hazard maps (Barberi et al., 1990; Wadge et al., 1994; Kauahikaua et al., 1995; Connor et al., 2001; Saito et al., 2001; Alberico et al., 2002; Esposti Ongaro et al., 2002; Cioni et al., 2003; Hurst and Smith, 2004; Rosano et al., 2004; Magill and Blong, 2005; Renschler, 2005; Toyos et al., 2007).

We consider that any methodology for the elaboration of a volcanic hazard map, for a specific volcanic area and a specific time interval, should contain first a correct identification of the expected volcanic and related processes. This information should come from a detailed geological and morphological (topographic) reconstruction of the area under study. Once the potential hazards have been identified, the following steps should be computed for each expected hazard: a) Evaluation of the temporal probability for the occurrence of the hazard during the considered time interval, b) Definition of the source area and, if required, computation of probability of vent opening (volcanic susceptibility), c) Characterization of the expected eruption, d) Numerical simulations of eruptive process, and e) Elaboration of the hazard map (Fig. 1).

2.1. Identification of expected hazards

Selection of the hazards that can be expected in a volcanic area during a specific time interval should be

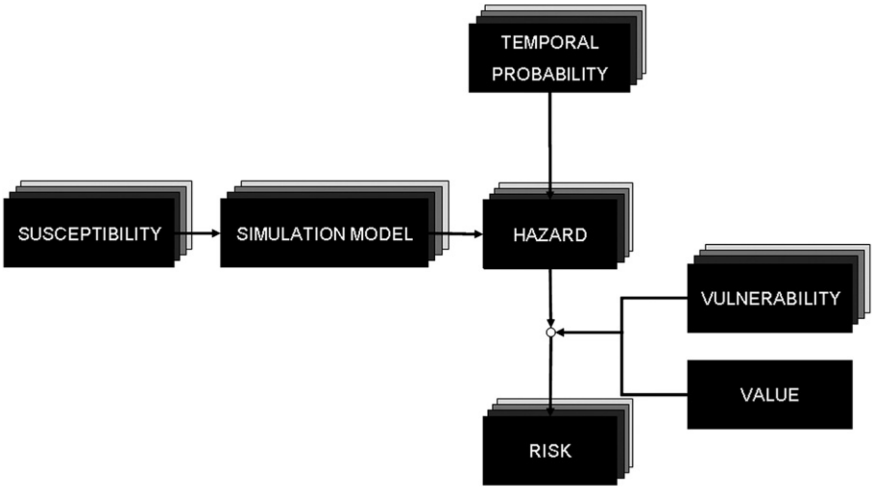


Fig. 1. Schema for the elaboration of volcanic hazard and risk maps. Stacked rectangles corresponding different hazards.

based on a good knowledge of eruptive history of the area. For long-term analysis, the detailed geological reconstruction of past eruptions and of their structural constraints will constitute the main source of information. The stratigraphy of the products of past eruptions will help to reconstruct their eruption sequences and allow us to determine the characteristics of the main processes that have occurred during such eruptions. The identification of the source region (vent area) for each eruption, in addition to the topographic characteristics of the terrain, is also of crucial importance to constraint the potential hazards that can be expected in the future. For very short-term analyses (i.e. in case of a volcanic unrest), data provided by the monitoring networks should also be taken into account, as they could constrain the source region and, consequently, the hazards that can be expected in that short-time period.

2.2. Evaluation of the temporal probability for the occurrence of the hazard

As in the previous step, this evaluation is made based on the eruptive history of the area. Different methodologies have been proposed for computing the probability of a future eruption, both for long-term (see for example Martin et al., 2004) or short-term analysis, when the probability can be estimated from an event tree (Newhall and Hoblitt, 2002; Marzocchi and Zaccarelli, 2006).

2.3. Definition of the source area

Depending on the characteristics of the active volcanic area under study, the area that can host future eruption centres can be wide or restricted to a few or even a single vent. If we just consider a specific stratovolcano, such Etna or Vesuvius, we can assume that a future eruption will occur from a central vent or close to it along the flanks of the volcano. However, if we consider a volcanic area like Tenerife, where eruptions of basaltic and phonolitic magmas have occurred at the same time from peripheral rift zones and from the Teide central complex respectively (Ablay and Martí, 2000), selecting future vents is not so simple. In such cases, it will be necessary to evaluate the spatial probability of hosting future emission centres (i.e. the volcanic susceptibility) for each of the parcels (pixels) of the area. This aspect is described in more detail in Section 7.

2.4. Characterization of expected eruption

The expected eruption should be characterised in terms of the input parameters required by the simulation models employed for the expected hazards. The available information can condition the selection of the model to be used, as the complexity of the models will determine the number of input parameters required. Very complex models may require a high number of parameters that in most cases cannot easily be assessed. Very often, the characterization of expected eruptions is made by selecting a well-studied eruption that can be considered representative of the volcano behaviour.

2.5. Numerical simulations of hazard

Once the corresponding simulation model of the expected hazard is selected, numerical simulations should be computed. Usually, this involves running a high number of simulations, either because of the size of the area susceptible of hosting a new vent or because of the characteristics of some of the input parameters required by the model (for example, if a hazard map for ash fallout is being elaborated, simulation for different wind fields should be computed). Numerical simulation models should be simple enough, so they should not have complex computational requirements, but also sufficiently accurate to represent the influence of their first order controlling parameters on the outputs. The equilibrium between these two requirements is one of the most difficult aspects to be achieved in the development of e-tools for hazard assessment, as most of the volcanic hazards are governed by complex systems of non-lineal equations, which should be simplified into the numerical simulation models required for volcanic hazard assessment.

2.6. Elaboration of the hazard maps and eruption scenarios

Finally, the probability of vent opening, the temporal probability, and the results obtained from the numerical simulations, are processed in order to obtain a final map showing for each point the probability of being affected by the considered hazard during the considered time interval. Sometimes, particularly on those volcanoes with a very short historical eruptive record, it is very difficult to asses the temporal probability of occurrence of the considered hazard. In that case, if the methodology is followed neglecting step 2.2., the hazard maps obtained can be considered hazard maps lato sensu, as they only need a scale factor to become hazard maps stricto sensu, i.e. the probability values obtained make sense as relative values between different points, or the hazard map can be considered a hazard map stricto

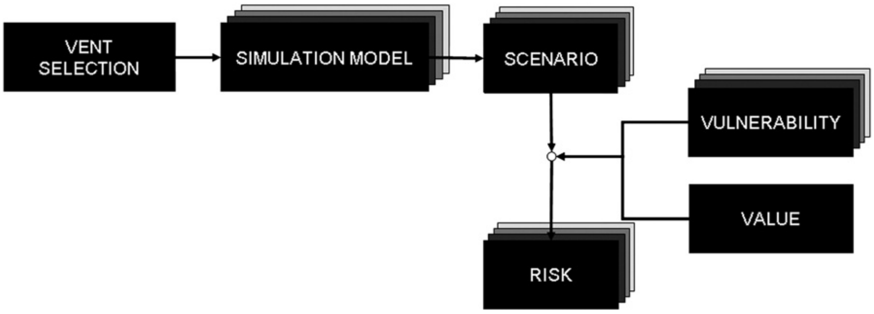


Fig. 2. Schema for the elaboration of volcanic scenarios and computation of associated risk. Stacked rectangles mean different hazards.

sensu assuming that the probability of occurrence of the considered hazard for the time interval selected is one.

The methodology for the elaboration of a scenario map is much simpler, as a scenario reflects the effects of a single eruption, usually with a unique vent. Therefore, a scenario will consist on the numerical simulation of all the expected hazards of the eruption (see Fig. 2).

In this methodology, it is clear the large amount of information required for the elaboration of a volcanic hazard map or an eruption scenario. Efficient management of this volume of data requires specific systems. As most of the information is georeferenced, the appropriate framework for processing this kind of data is through a Geographical Information System (Gómez-Fernández, 2000; Pareschi et al., 2000). However, although nowadays GIS include many tools for modelling and hazard analysis, the numerical models for the simulation of eruptive processes cannot usually be implemented using only GIS tools and functions.

Therefore, the main objective of this paper is the development of a GIS-based tool that allows automation of most of the steps of the methodology described above. Particularly, the tool presented in this paper automates the methodology from step 2.3 forward.

3. Integration of numerical simulation models of eruptive processes into the GIS

As shown in Figs. 1 and 2, the numerical simulation models of eruptive processes are the core of our methodology for the elaboration of volcanic hazard maps and eruption scenarios. Therefore, one of the most important aspects to take into account in the design of the system was the integration of the numerical simulation models of volcanic and related hazards into the GIS. The main requirements for this integration were the efficiency in computational time, the ease for including new models, and to leave the tool opened

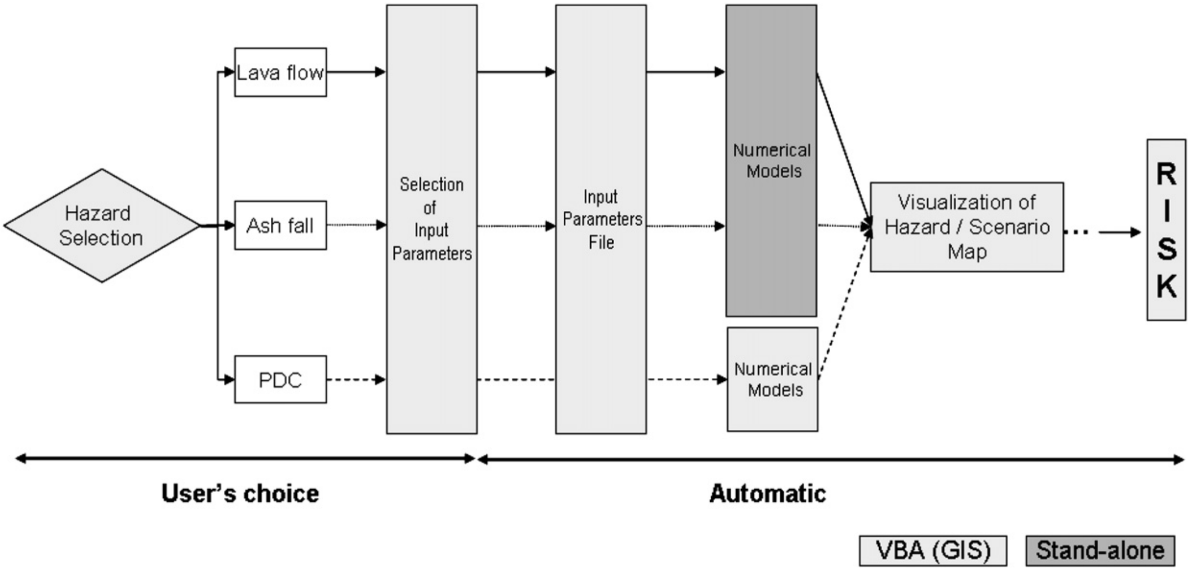


Fig. 3. Schema for the integration of numerical models into the GIS. Automotion of hazard analysis enables subsequent automation of related risk analyses.

for future new analysis (for example, risk computations or vulnerability maps).

The GIS initially selected for the development of the automatic system was ArcView™ 8.2 by ESRI® (with Spatial Analyst extension) due to its widely spread use and to the fact that it allows a high degree of customization through Visual Basic for Applications© (VBA). However, the system can be easily upgraded to be used in the newer versions of ArcView™.

Some tests have been performed in order to optimize the structure of the system. It was found that the best structure was implementing the numerical simulation models out of the GIS, in such a way that they read the input parameters from an ASCII file and that the output they give was compatible with ESRI® formats (Fig. 3). This gives two main benefits: first, it allows each model developer to optimize his code in terms of computational time and, second, it makes inclusion of new models into the system rather easy, as almost no re-writing of the code has to be done. Only very simple models, such as the energy cone model (for simulation of pyroclastic density currents), can be effectively implemented inside the GIS, as, from the numerical point of view, they can exploit many of the spatial functions of the GIS.

The user interfaces have been designed in VBA, and a customized toolbar (Fig. 4) has been created, for the users to access the numerical models. Once one hazard has been chosen, the input parameters required by the model can be interactively selected, both by clicking on different maps of the volcanic area and numerically. The user can then choose between computing a volcanic scenario (i.e. one single vent) and a hazard map (usually multiple possible vents with different probability). The system then launches the corresponding numerical model and, when finished computation, it returns the control to the GIS. Then, the result is shown as a new layer in the original map. This final result is stored on the disk together with a file containing all the input parameters used in the simulations.

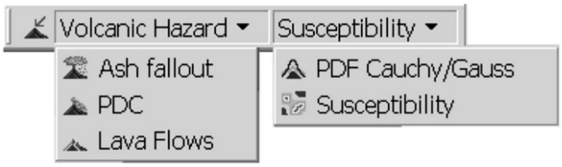


Fig. 4. Customized toolbar of the system. From left to right: icon for interactive vent selection, volcanic hazard menu (access to the implemented hazards: ash fallout, pyroclastic density currents and lava flows) and susceptibility menu (access to a tool for the computation of the PDF based on kernel techniques and another for the multicriteria evaluation of the susceptibility).

In order to check the functionality of the system, simple models for the simulation of three volcanic hazards (lava flows, ash fallout and pyroclastic density currents) have been included in the tool. The structure of the tool allows integration of any model with a little programming effort, as virtually only the user interface should be developed. The inclusion on the system of different models for the same hazard will permit comparing the adequateness of each model for hazard assessment.

4. Lava flows

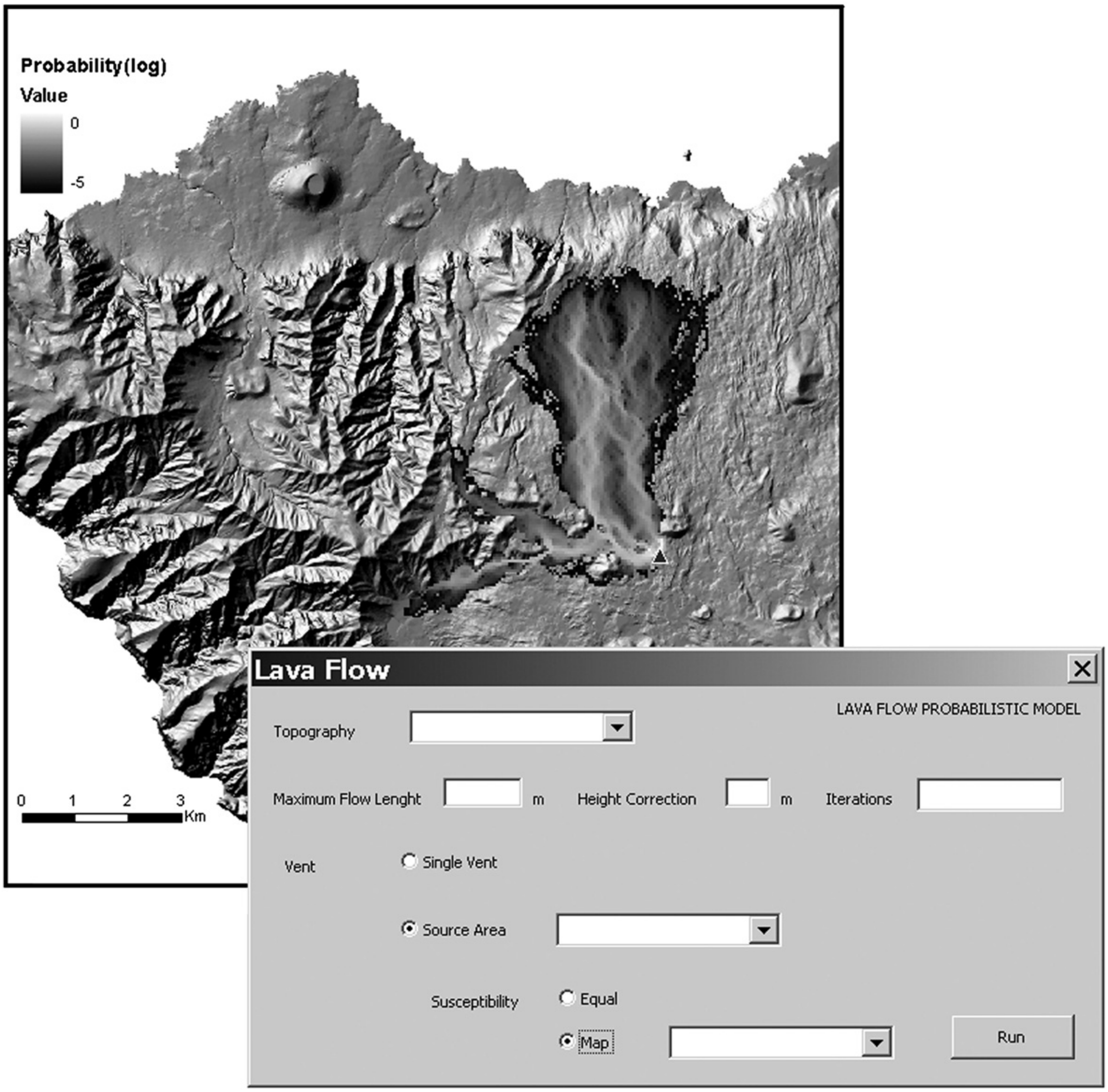
The model selected for the numerical simulation of the area that can be covered by a lava flow is one of those called "maximum slope models". These models assume that the topography plays the major role on determining the path that a lava flow will follow. Therefore, considering a Digital Elevation Model (DEM), the probability that the flow propagates from one cell to one of his eight neighbours is proportional to the difference in height between the neighbour and the cell (correcting this last one summing a factor named "height correction") and only greater than zero if this difference is positive. The selection of the cell where the flow will propagate is made by means of a MonteCarlo algorithm. The maximum flow length is limited by a parameter whose value is constant for all runs. If a great number of possible paths for the flow is computed, the counting of how many of them have crossed a cell is proportional to the probability of that cell being covered by lava. Therefore, the output of the model is a map where the value of each cell is its probability of being invaded by the flow. A complete description of the model can be found in Felpeto et al. (2001).

The input parameters window is shown in Fig. 5. Topography should be selected from a popup menu that shows all the raster layers in the current map. The characteristics of this dataset (extent, projection, number of rows and columns,… etc.) will be those of the output raster. The global parameters such as maximum flow length, height correction and iterations per vent, should be entered numerically. The user can select between a single vent (for a scenario) and a source area. In the first case, the coordinates of the vent can be entered numerically or interactively, clicking on the map. In the case of multiple possible vents, a raster layer should be selected, where all non-zero cells will be considered emission centres. Then, the susceptibility for those vents should be selected, choosing "equal" if all the cells from the source area have the same probability of hosting a new vent or selecting a raster layer whose values correspond to the susceptibility of each cell. Fig. 5 also shows an example of the output of the lava flow simulation for a scenario of a basaltic eruption on Tenerife, with vent location on the Santiago rift, which hosts most of the historical basaltic vents.

5. Ash fallout

The numerical model selected for the simulation of the ash fallout is an advection–diffusion model (Folch and Felpeto, 2005), where the vertical mass distribution is computed using the Suzuki's approximation (Suzuki, 1983). The model considers that the particles fall at their terminal fall velocity, calculated from size, density, Reynolds number and drag coefficient, assuming standard atmosphere up to the tropopause and isothermal atmosphere for higher altitudes. During its deposition, they are advected by horizontal winds and diffused horizontally due to atmospheric turbulence (i.e. the model neglects both the vertical wind component and vertical diffusion). The output of the model is two maps, one showing the expected ash thickness, and the other, the expected ash load.

Fig. 6 shows the input parameters window of the ash fallout model. As this model requires many more input parameters than the previous one, to avoid possible errors by the operators, some of the parameters appear in



Lava Flow

LAVA FLOW PROBABILISTIC MODEL

Topography

Maximum Flow Lenght m

Height Correction m

Iterations

Vent ○ Single Vent

● Source Area

Susceptibility ○ Equal

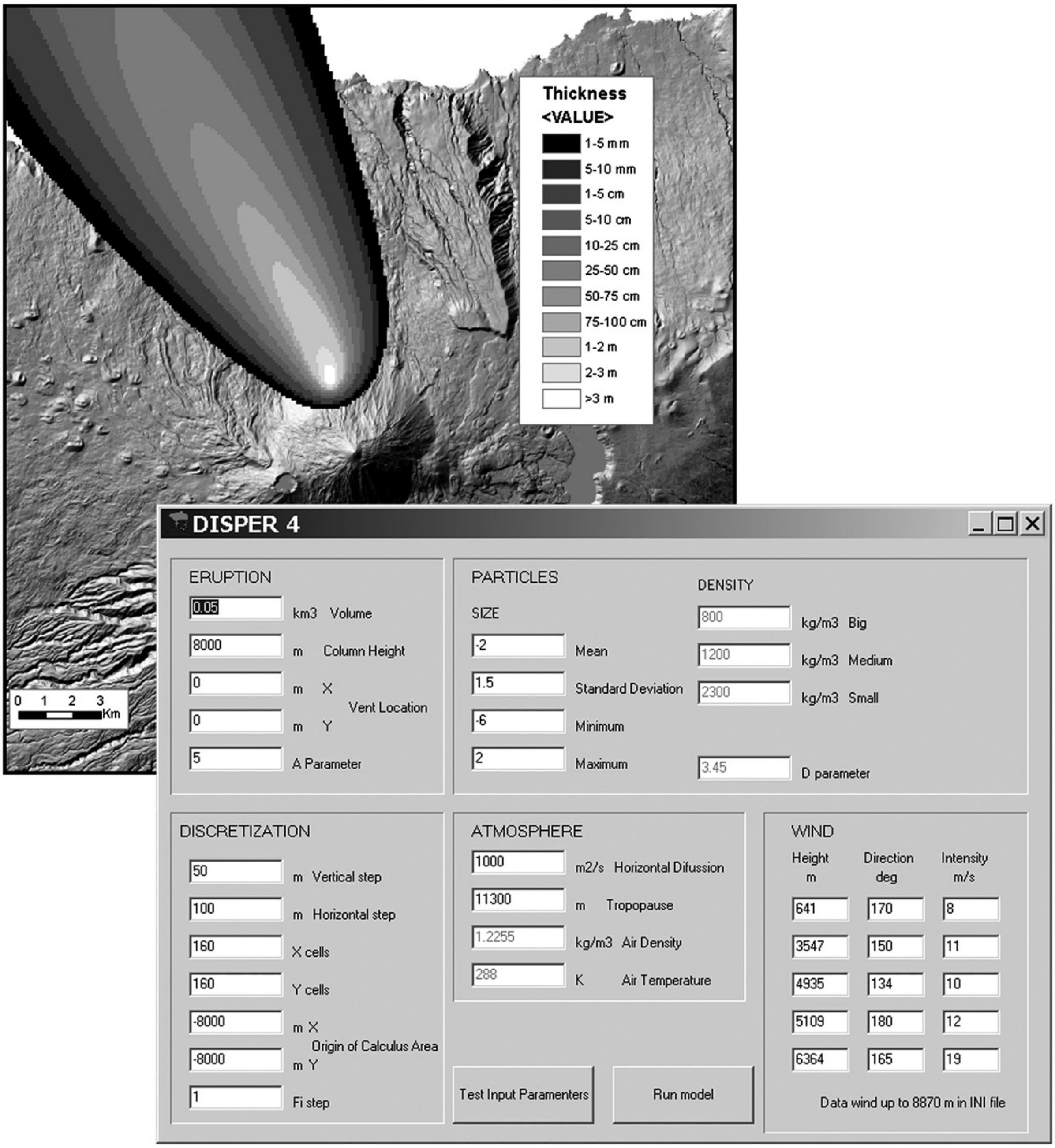
● Map

Fig. 5. Right lower corner: input parameters window for lava flow simulation model. Back: example of the output of the lava flow model for a scenario with vent location at the small triangle and over a 50 m DEM of Tenerife Island (Canary Islands).

grey and cannot be changed from that window. Nevertheless, those values can be modified through direct access to the initial input parameters file. On the same figure, an example of the output of the model for ash thickness is shown for a subplinian event with the vent located on the northern flank of Teide volcano, using the same eruption parameters that those deduced for the 2000 bp Montaña Blanca phonolitic eruption (see Ablay et al., 1995; Folch and Felpeto, 2005).

6. Pyroclastic density currents

The numerical model selected for the computation of the area potentially affected by a pyroclastic density



DISPER 4

ERUPTION

0.05 km3 Volume
8000 m Column Height
0 m X
0 m Y
Vent Location
5 A Parameter

PARTICLES

SIZE

-2 Mean
1.5 Standard Deviation
-6 Minimum
2 Maximum

DENSITY

800 kg/m3 Big
1200 kg/m3 Medium
2300 kg/m3 Small
3.45 D parameter

DISCRETIZATION

50 m Vertical step
100 m Horizontal step
160 X cells
160 Y cells
-8000 m X
-8000 m Y
Origin of Calculus Area
1 Fi step

ATMOSPHERE

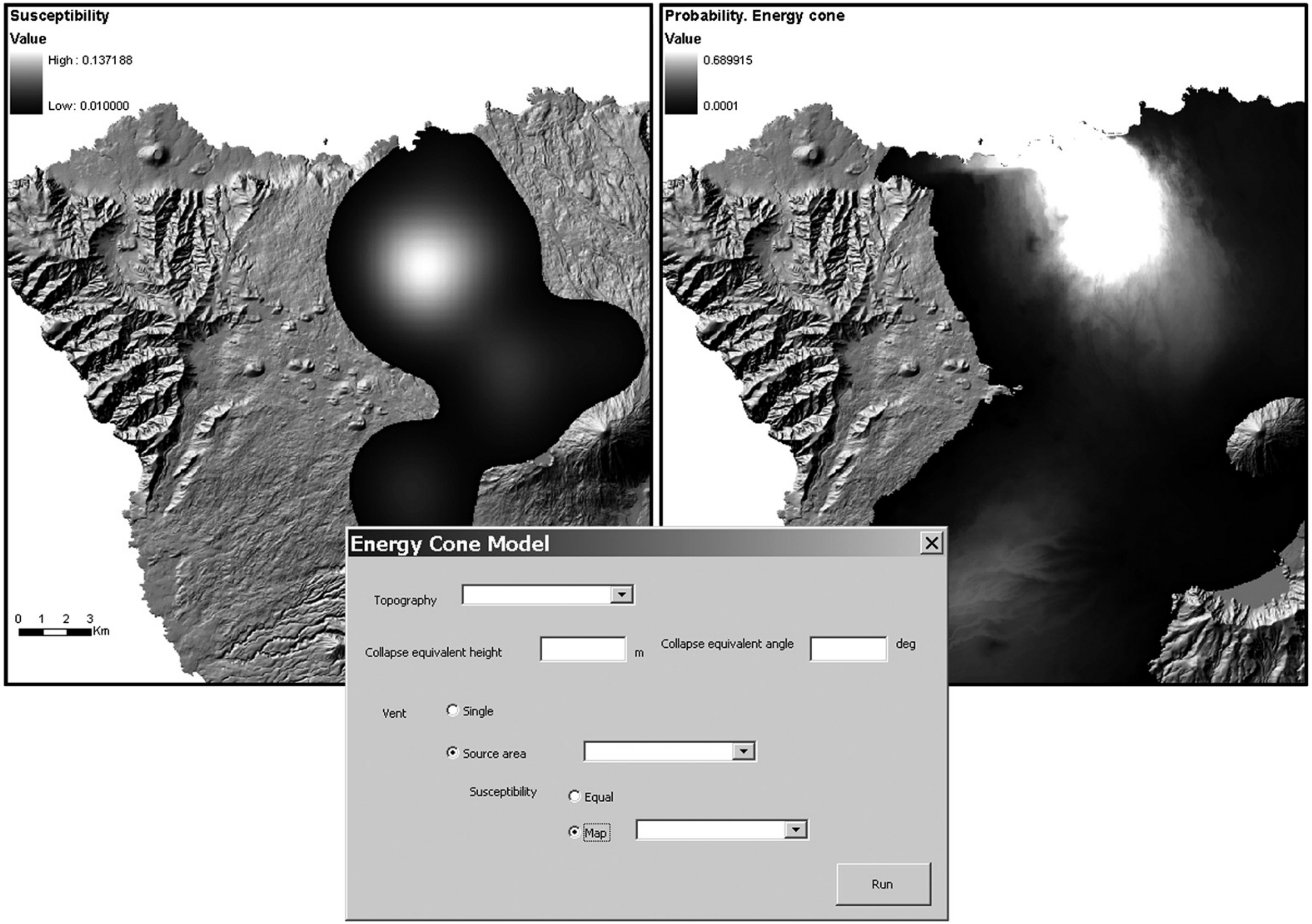
1000 m2/s Horizontal Difussion
11300 m Tropopause
1.2255 kg/m3 Air Density
288 K Air Temperature

WIND

Height m	Direction deg	Intensity m/s
641	170	8
3547	150	11
4935	134	10
5109	180	12
6364	165	19

Data wind up to 8870 m in INI file

Fig. 6. Left lower corner: input parameters window for ash fallout simulation model. Back: example of the output of the ash fallout model (ash thickness) for a scenario with vent location at the northern flank of Teide volcano on Tenerife Island (Canary Islands).



Topography

Collapse equivalent height m

Collapse equivalent angle deg

Vent ○ Single

● Source area

Susceptibility ○ Equal

● Map

Fig. 7. Upper right corner: example of hazard map for PDC on Tenerife Island. The source area for the PDC are the non-zero values of the susceptibility map on the upper left corner. Front: input parameters window for PDC simulation model.

current (PDC) is based on the energy line concept, firstly applied to pyroclastic density currents by Malin and Sheridan (1982). It uses the concept of "energy line" that links the emission centre plus a certain altitude with the distal limit of the flow deposit. The tangent of the angle of this line relative to the horizontal represents the resistance due to the friction (Sheridan and Malin, 1983). An implementation of this model has been done directly in VBA inside the GIS (Toyos et al., 2007). The output of the model is the maximum potential extent that can be affected by the flow. It also can derive maps of flow velocity or dynamic pressure (both only for scenario option) following the methodology proposed in Toyos et al. (2007).

The input parameters window for this model (Fig. 7) is very similar to that of the lava flow model, as it also allows users to assign global input parameters for the numerical simulations and to choose between perform a scenario map (single vent) and a hazard map (both with constant and variable probability for vent opening). Fig. 7 also shows an example of hazard map (lato sensu) for PDC for the NW area of Tenerife using the source area shown in the susceptibility map on the upper left corner.

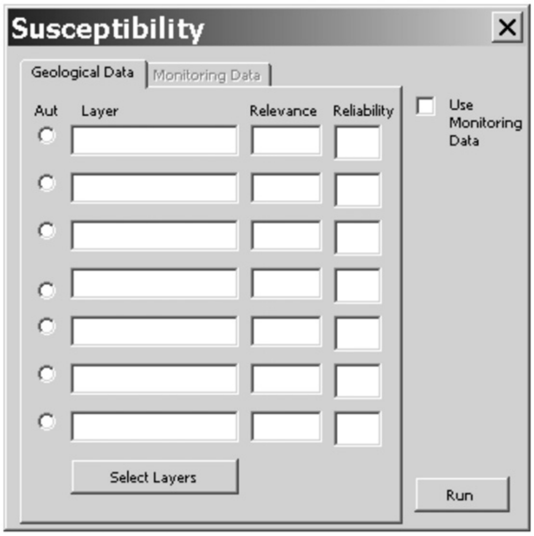


Fig. 8. Input parameters window for the computation of volcanic susceptibility. In the first page named "Geological Data", different raster layers already loaded in the map can be selected by clicking on the "Select Layers" button, and their corresponding values of relevance and reliability assigned. If the checkbox "Use Monitoring Data" is checked, the second page named "Monitoring Data" becomes available. This page is very similar to the first but also includes a box for entering the relevance value assigned to the whole monitoring data with respect to the geological data.

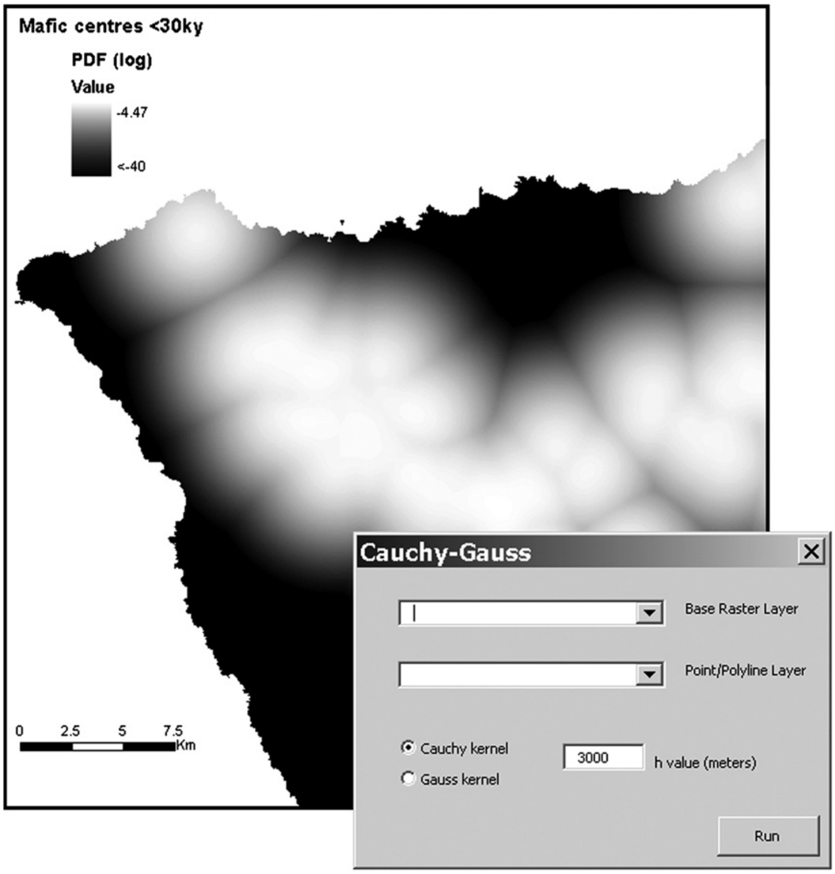
7. Susceptibility tools included in the system

The spatial probability of vent opening, named here as volcanic susceptibility, can be a critical step for the evaluation of the volcanic hazard (Martin et al., 2004; Jaquet et al., 2006; Marzocchi and Zaccarelli, 2006; Martí et al., submitted for publication), two tools for its computation have been included in the system. The tool named "Susceptibility" allows the multicriteria computation of the volcanic susceptibility following the methodology proposed in Martí et al. (submitted for publication). This methodology considers that the evaluation of mid/long-term (years to decades) susceptibility should be computed based on data somehow related to the stress field of the area, as this is the fact conditioning the path for the magma to reach the surface. All the available datasets that can provide information on this issue should be taken into account (for example, location of vents, fractures, vent alignments, structural data provided by different geophysical techniques,... etc.), and each of them should be converted into a probability density function (PDF), normalized through the whole area of study. Each of the PDFs should be given a relevance value (that measures its importance in the evaluation of the susceptibility) and a reliability value (that measures the quality of the dataset with respect to the evaluation of the susceptibility). Those PDFs and values are combined assuming a non-homogeneous Poisson process to obtain the final probability map (i.e. the susceptibility map).

If susceptibility maps are being computed for short-term analyses (from days to a few months), data provided by monitoring networks should also be taken into account. The procedure for the evaluation of the PDF corresponding to monitoring data is the same described above for mid/long-term susceptibility. Once the PDF enclosing all the available monitoring datasets has been calculated, it is combined with the mid/long-term susceptibility map, with an assigned relevance to obtain the final short-term susceptibility map. Fig. 8 shows the input parameters window for the evaluation of the susceptibility.

One of the most important points in the evaluation of the susceptibility is how to convert any dataset into a PDF. This question has no unique answer, as the relationship between one dataset and the spatial probability for the opening of a new vent depends on the characteristics of each dataset. A common topic in the scientific literature is the relationships between vent locations and corresponding PDFs (see, for example, Wadge et al., 1994; McBirney et al., 2003; Martin et al., 2004; Jaquet et al., 2006).

The tool named "PDF Cauchy/Gauss" calculates a PDF from a point or line layer, following the procedure



Cauchy-Gauss

Base Raster Layer

Point/Polyline Layer

● Cauchy kernel

○ Gauss kernel

3000 h value (meters)

Fig. 9. Right bottom corner: Input parameters window for the susceptibility tool “PDF Cauchy/Gauss”. The upper popup menu allows the user to select a raster layer whose characteristics will be those of the output raster. The second popup menu allows selection of a layer containing points or lines as input data for the computation of the PDF. The user can select between Cauchy or Gauss kernels and input the smoothing parameter (h). Back: example of the output from the tool for the mafic centres younger than 30 ky on Tenerife Island.

described in Martin et al. (2004) for evaluating the probable location of vents. This method assumes that the probability of hosting a new vent can be computed from the spatial distribution of vents with kernel estimation techniques, considering Gauss or Cauchy kernels. Fig. 9 shows the input parameters window of the tool and a sample of the output for young mafic vents on Tenerife Island.

8. Discussion and conclusions

We have presented a new automatic system specifically developed to elaborate volcanic hazard maps and eruption scenario maps in a simple, friendly, and economical way. The aim of the system is to facilitate the task of territorial planners and risk managers when dealing with active volcanic areas.

The simplicity of the system’s structure implies some limitations, in particular for what concerns to the complexity of the simulation models we can use to describe volcanic hazards and their potential effects. In fact, very complex numerical simulation models, which require highly sophisticated computational techniques, are not able to be included in the system. However, this does not preclude obtaining a first order hazard assessment of the area under study in a very short time and using standard computational facilities. The development of automatic systems similar to the one we are introducing here, should lead to the standardization of protocols for hazard assessment and risk management, facilitating the tasks of scientists and technicians in charge of such responsibility and the exchange of information between the different working groups.

One of the most interesting possible extensions of our automatic system would be to have near real-time access to different datasets. First, volcanic monitoring data, for the evaluation of short-time susceptibility maps and continuous update of the expected scenarios in the case of unrest. Second, real-time access to meteorological data in order to generate expected short-term eruptive scenarios for ash fallout. Required data would be short-term (days) wind field forecasts. This would allow the system to generate tephra fallout scenarios for the following days, and to continuously update them.

The automation of the generation of volcanic scenarios and hazard maps inside a GIS system allows subsequent automation of the related risk analyses, such as evaluation of economic losses to buildings, crops, … etc, status of main roads (for testing evacuation routes), … etc. Therefore, integrated systems such as the one proposed in this paper can make GISs a useful tool for the evaluation and management of volcanic risk.

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