Nat. Hazards Earth Syst. Sci. Discuss., 3, 1835–1860, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/1835/2015/
doi:10.5194/nhessd-3-1835-2015

Natural Hazards and Earth System Sciences
Open Access
Discussions

Sensibility analysis of VORIS lava-flow simulations: application to Nyamulagira volcano, Democratic Republic of Congo

A. M. Syavulisembo[1], H.-B. Havenith[2], B. Smets[3,4,5], N. d'Oreye[3,6], and J. Marti[7]

[1]Goma Volcanological Observatory, Goma, DR Congo
[2]University of Liège, Department Geology, Sart Tilman B52, 4000 Liège, Belgium
[3]European Center for Geodynamics and Seismology, rue Josy Welter 19,
7256 Walferdange, Luxembourg
[4]Vrije Universiteit Brussel, Pleinlaan 2, 1085 Brussels, Belgium
[5]Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium
[6]National Museum of Natural History Geophysics/Astrophysics Department,
rue Josy Welter 19, 7256 Walferdange, Luxembourg
[7]Institute of Earth Sciences Jaume Almera, CSIC, Lluís Solé i Sabarís s/n,
08028 Barcelona, Spain

Received: 26 November 2014 – Accepted: 8 January 2015 – Published: 10 March 2015

Correspondence to: A. M. Syavulisembo (adalmuhindo@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Assessment and management of volcanic risk are important scientific, economic, and political issues, especially in densely populated areas threatened by volcanoes. The Virunga area in the Democratic Republic of Congo, with over 1 million inhabitants, has to cope permanently with the threat posed by the active Nyamulagira and Nyiragongo volcanoes. During the past century, Nyamulagira erupted at intervals of 1–4 years – mostly in the form of lava flows – at least 30 times. Its summit and flank eruptions lasted for periods of a few days up to more than two years, and produced lava flows sometimes reaching distances of over 20 km from the volcano, thereby affecting very large areas and having a serious impact on the region of Virunga. In order to identify a useful tool for lava flow hazard assessment at the Goma Volcano Observatory (GVO), we tested VORIS 2.0.1 (Felpeto et al., 2007), a freely available software (http://www.gvb-csic.es) based on a probabilistic model that considers topography as the main parameter controlling lava flow propagation. We tested different Digital Elevation Models (DEM) – SRTM1, SRTM3, and ASTER GDEM – to analyze the sensibility of the input parameters of VORIS 2.0.1 in simulation of recent historical lava-flow for which the pre-eruption topography is known. The results obtained show that VORIS 2.0.1 is a quick, easy-to-use tool for simulating lava-flow eruptions and replicates to a high degree of accuracy the eruptions tested. In practice, these results will be used by GVO to calibrate VORIS model for lava flow path forecasting during new eruptions, hence contributing to a better volcanic crisis management.

1 Introduction

During the past century Nyamulagira (or Nyamuragira), the westernmost volcano of the Virunga Volcnaic Province (VVP), erupted at least 30 times at intervals of 1–4 years (Tedesco, 2002, 2003; Smets et al., 2010). It is considered one of the most active African volcanoes, with at least 39 documented eruptions since 1882 (Smets et al., 2013). Most of historical eruptions of Nyamulagira occurred along its flanks, sometimes more than 10 km far from the central edifice. Nyamulagira eruptions commonly last few days to few weeks, but some voluminous and less frequent historical events lasted more than 2 years (Pouclet, 1976; Smets et al., 2010). Nyamulagira's activity is characterized essentially by lava fountaning activity along an eruptive fissure, which produces lava flows and progressively build, together with ejected tephra, a spatter-and-scoria cone along the fissure (Pouclet, 1976; Smets et al., 2013)

On 2 January 2010, an eruption of Nyamulagira started in the central caldera and along the SSE flank, emitting $\sim 45.5 \times 10^6\,\mathrm{m}^3$ of lava. These lava flows caused an enormous loss of vegetation in the Virunga National Park and the dense plume of gases that scaped from the eruptive vents affected the surrounding population. The estimated surface area covered by the 2010 lava flows is $15.17 \pm 2.53 \times 10^6\,\mathrm{m}^2$ (Smets et al., 2013).

Due to the presence of densely populated zones and a National park in the vicinity of Nyamulagira, hazards associated with its frequent fissural eruptions must be assessed. In addition to detailed field surveys and literature reviews performed to better characterise Nyamulagira's eruptive activity and, hence, better assess eruption hazards, simulations are practical tools to create hazard maps and detect the most probably affected areas during an eruption. For lava flows a wide diversity of both probabilistic and deterministic simulation models exist in the volcanological literature (e.g. Crisci et al., 1986, 1997; Ishihara et al., 1989; Wadge et al., 1994; Kuauhicaua et al., 1995; Felpeto et al., 2001; Favalli et al., 2005; Damiani et al., 2006) and offer different degrees of accuracy depending on the mathematical methods used to make calculations and the input parameters considered. Unfortunately, most of these models only exist in the scientific literature and their source codes are not freely available. Furthermore, some require complex calculations and significant CPU usage, which is not always available.

Felpeto et al. (2007) have built a volcanic hazard assessment software package (VORIS 2.0.1) within ArcGIS 9.1 (©ESRI), which includes a probabilistic lava-flow model based on a previously developed model (Felpeto et al., 2001). Unlike existing lava-flow models, VORIS is free (downloadable from www.gvb-csic.es), easy-to-use and does not entail high computing requirements. However, VORIS may be less accurate than other more sophisticated deterministic lava-flow simulation models, which thus creates a dilemma as to whether a high precision or a quicker, easier-to-use – but less precise – tool is preferable.

The Goma Volcano Observatory (GVO) is in charge of conducting volcano monitoring and assessing volcanic hazards in the Democratic Republic of Congo (DRC). Thus, as part of its work, it needs to adopt adequate methodologies and tools – tried and tested in other areas – that can be used by its scientists and technicians to comply with the most essential of its tasks. To check whether VORIS could be of use to the GVO for lava flow hazard assessment in the DRC volcanoes, and for quickly estimating the potential impact of new lava flows in the event of a new eruption, we tested this package's lava-flow simulation model by replicating the Nyamulagira 2010 eruption, most of whose parameters and pre-eruption topography are known.

2 Geological setting

The VVP is part of the western branch of the East African Rift and is situated between Lake Edward in the north and Lake Kivu in the south (Fig. 1) (Verhoogen, 1938; Smets, 2007). It is composed by eight large volcanic edifices: Muhabura (4127 m), Gahunga (2474 m), Sabinyo (3647 m), Visoke (3711 m), Karisimbi (4507 m), Mikeno (4437 m), Nyamulagira (3058 m), and Nyiragongo (3470 m) (Komorowski et al., 2003). Although volcanic activity in the VVP dates back to the Upper Miocene (Pouclet, 1977), Nyiragongo and Nyamulagira are currently the main active volcanoes of this volcanic province (Tedesco et al., 2007; d'Oreye et al., 2012).

Nyamulagira (1.41° S, 29.20° E) is located in the Virunga National Park, which was declared as a World Heritage Site in 1979 and has an endangered one since 1994 (http://whc.unesco.org/fr/list/63). This composite volcano produces alkali basalts, hawaiites, basanites, and tephrites, with a SiO_2 content ranging from 43 to 56 wt %

(Aoki et al., 1985). In recent decades, the eruptive activity took the form of periodic flank fissure-fed effusive eruptions, with intervals of summit lava lake activity (e.g. Hamaguchi and Zana, 1983; Wadge and Burt, 2011; Smets et al., 2014), but since April 2014, it is restricted to episodic fountaining and lava lake activity in a pit crater located in the NE sector of the central caldera (Smets et al., 2014).

3 Methodology

We used VORIS 2.0.1 (Felpeto et al., 2007; http://www.gvb-csic.es) to simulate the lava flows emitted by Nyamulagira during the 2010 eruption. VORIS (Volcanic Risk Information Systems) was developed in an ArcGis 9.1 (©ESRI) Geographical Information System (GIS) framework and allows eruptive scenarios and probabilistic hazards maps to be created rapidly for the commonest volcanic hazards (lava flows, fallout and pyroclastic density currents).

The lava flow model included in VORIS is a probabilistic (Monte Carlo algorithm) model based on the assumption that both topography and flow thickness play major roles in determining the path followed by a lava flow (Felpeto et al., 2007 and references therein). The model computes several possible paths for the flow on the basis of two simple rules: (i) the flow will only propagate from one cell to one of its eight neighbors if the difference in corrected topographic height between them is positive, and (ii) the probability that the flow will move from one cell to one of its neighbors is proportional to the difference in height. The calculation of the probability of a point being invaded by lava is performed by computing several random paths using a Monte Carlo algorithm (see Felpeto, 2009 for more details).

The input data for this simulation includes a Digital Elevation Model (DEM), from which we can chose either a single vent or a vent area including several vents, the maximum flow length (i.e. the total length of the path followed by the lava flow, not just the maximum longitudinal distance), and a height correction (i.e. the average thickness of the flow). All these input parameters remain essentially constant during the simulation and characterize the resulting model. The maximum flow length and the height correction or average thickness are integers defined in meters. In addition, the "iterations number" must be considered. This number is proportional to the number of calculations made and will determine the CPU time required and the accuracy of the results obtained. However, the greater the number of iterations, the more accurate the results, but also the greater the risk that the microprocessor will be overloaded. This is why in our study we paid special attention to this input parameter in order to determine the most appropriate number of iterations for guaranteeing obtaining reliable results without using too much computing time.

The DEM is a fundamental boundary condition needed for modelling volcanic processes and associated risks including pyroclastic, lava, and mud flows (Sheridan et al., 2004). In this case study, the DEM plays a major role in determining the pathways of lava flows (Felpeto et al., 2007) as it is the numerical base used to compute the path the lava will follow based on the principle used by VORIS. To test the model, we used three different DEMs corresponding to the 2010 pre-eruption topography: SRTM1, SRTM3, and ASTER GDEM. They differ either by their resolutions or by the way they were produced. SRTM (Shuttle Radar Topography Mission). DEMs were produced by radar interferometry, using radar images acquired during a space mision, with NSA, space shuttle. SRTM1 in the studied area has a spatial resolution of 31 m, while that of SRTM3 has 93 m-wide pixels. In recent years, SRTM DEMs were the main source of height data for the VVP. The ASTER GDEM (ASTER Global Digital Elevation Model) is not obtained by stereophotogrametry, using nadir and backward images acquired by ASTER (Advanced Spaceborne Thermal Emission and Felection Radiometer) optical sensor, on board the Terra satellite (NASA/MATI/J-Spacesystems). ASTER GDEM data are published with a spatial resolution of 30 m (Hormann, 2012).

In order to carry out a sensibility analysis of the input parameters we conducted several simulations using different DEMs, different values for the flow lengths and average lava-flow thicknesses, and different numbers of iteration. The comparison of the results obtained with the three different DEMs is important for testing the suitability of each model in this type of lava-flow simulations and for testing their aptness for using with VORIS. In equatorial zones, such as in the VVP, the quality of the ASTER GDEM is considerably affected by cloud cover. As a aconsequence, artifacts apperar in the lava fields (Arefi and Leinartz, 2011). Compared to different GIS ground control points acquired in the southern Nyragongo lava field (Albino et al., 2014), the SRTM DEM has a better vertical accuracy than the ASTER GDEM. Hense, it is initially expected to have more reliable results using the SRTM DEMs.

4 Simulations and sensibility analysis of input parameters

4.1 Total length

The sensibility of the length parameter was evaluated using SRTM1 and 12 different simulations. A vent location was fixed at point A (UTM 35S 746161E/9840963N) with an average lava flow thickness of 3 m; 5000 iterations were applied with a different length value for each: L1 = 1 km, L2 = 5 km, L3 = 10 km, L4 = 15 km, L5 = 20 km, L6 = 25 km, L7 = 30 km, L8 = 35 km, L9 = 40 km, L10 = 45 km, L11 = 50 km, and L12 = 55 km. The results obtained are given in Figs. 2 and 3 and in Table 1 with the values for the following parameters:

1. "True lava flow pixels": number of pixels of the DEM actually covered by the lava flow we are trying to simulate,
2. "Simulated pixels": number of pixels of the DEM corresponding to the surface covered by the simulated lava flow,
3. "Well-estimated pixels": number of pixels of the DEM corresponding to probable pixels that coincide with true pixels,
4. "Under-estimated pixels": number of pixels of the DEM corresponding to true pixels that were not covered by probable pixels,

5. "Outside true pixels": number of pixels of the DEM corresponding to probable pixels that do not coincide with true pixels,
6. "Length parameter": value of the input parameter "length" introduced into the model for the simulation,
7. "Modeled likely length": maximum longitudinal length of the simulated lava flow,
8. "Running time": the time that it took the model to generate the results.

The results obtained reveal that a too small length value underestimates the probability of being covered by the lava flow (simulation L1), while a too large value (simulation L12) tends to overestimate the maximum longitudinal or run-out distance, as well as the lateral extent, of the lava flow, given that the real eruption will stop before reaching this total maximum length. However, simulations L7 and L8, which considered intermediate maximum lengths of 30 and 35 km, respectively, match well the extent and run-out distance of the Nyamulagira 3 January 2010 lava flow. This indicates that, in this case and with the SRTM1 DEM, the total length of this lava flow was about double that of its longitudinal distance, thereby revealing the strong control that was exercised by the highly irregular topography characterized by non-rectilinear ravines and gullies.

4.2 Number of iterations

We arbitrarily selected 10 simulations with different numbers of iterations (I1 = 10, I2 = 50, I3 = 100, I4 = 500, I5 = 1000, I6 = 5000, I7 = 10 000, I8 = 50 000, I9 = 100 000, and I10 = 500 000). Simulations were carried out on SRTM1, with the same point A (UTM35S, 746161E/9840963N), which corresponds to the flank vent location of the 2010 eruption, and fixed average thickness and total length of 3 m and 33 km, respectively. The results obtained are shown in Figs. 4 and 5 and Table 2, and indicate that the number of simulated pixels, well-estimated pixels, and pixels outside the 2010 lava flow increase from simulations I1 to I6, but remain more or less constant from I6 to I10. Simulation I6 has the largest number of well-estimated pixels, the lowest number of under-estimated pixels, and a relatively low running (calculation) time. Even so, it still gives over 15 000 pixels that are outside the real lava flow. The number of iterations has less influence on the modeled lava flow length, with values ranging from 9.6 to 11.8 km.

4.3 Lava-flow thickness

In order to test the influence of the height correction parameter (average thickness) we performed eight simulations with different values of this parameter (i.e. h1 = 1 m, h2 = 2 m, h3 = 3 m, h4 = 4 m, h5 = 5 m, h6 = 6 m, h7 = 7 m, and h8 = 8 m). Iterations and total lengths were fixed to 5000 and 33 km, respectively. The results are presented in Figs. 6 and 7 and in Table 3. In these simulations (Figs. 6 and 7 and in Table 3) we noticed that, when the value of “h” increases, the effects of the relief decrease. In simulations h1–h8, the small zones enclosed by the true pixels decrease gradually in size until they are eliminated. Simulation h1 is too narrow and does not cover all the real lava flow, while simulation h8 produced an overflow outside the real lava flow. With the length parameter fixed to 33 km, we noticed that the modeled lava-flow length increases for simulations h1 and h2. Simulation h3 has the greatest number of simulated and well-estimated pixels, but the lowest number of under-estimated pixels.

4.4 DEM

Finally, we conducted several simulations to test the suitability of the different DEMs (S1: SRTM1, S2: SRTM3, and S3: ASTER GDEM) using vent location at point A (UTM35S 746161E/9840963N), lava thickness of 3 m, fixed number of iterations (5000), and 33 km for the length parameter. Results are shown in Figs. 8 and 9 and Table 4. Simulation S1 (using SRTM1) gives the best match between the modeled and natural lava flow, as it corresponds to the best calibration determined in the previous sections. In simulation S2, (SRTM3 DEM), lava spreads over a greater surface and clearly exceeds the area covered by the real lava flow. This result highlights the need to calibrate input parameters according to the DEM used in the simulation. The simulation S3 (ASTER GDEM) stopped prematurely because of strong artifacts present in the DEM. ASTER GDEM seems consequently not appropiate for lava flow modelling in the VVP.

5 Discussion and conclusions

We conducted several simulations of lava-flow emplacement using VORIS 2.0.1 (Felpeto et al., 2007), in order to replicate the lava flow emitted by the 2010 Nyamuragira eruption and to test the aptness of this model for conducting lava flow hazard assessment at the Nyamuragira volcano. Model calibration was performed by changing the values of the model parameters until simulations best mached the 2010 lava flow. Next, this calibrated simulation was realised on three DEMs to detect their influence on results.

This analysis shows that some input parameters can drastically change results. Too few iterations produce very poor results with a high degree of inaccuracy, while too many lead to considerable overestimates and a consequent increase in computing time. In our study, a number of iterations between 5000 and 10 000 gave the best results and the greatest degree of coincidence (up to 87 %) between the simulations and the real lava flow, with a total computing time of less than 20 min for each run. Simulations were less sensitive to changes in height correction (i.e. average thickness). However, we observed that the best results were obtained with a value of 3 m, which coincides with the average thickness commonly used to calculate of Nyamunragira lava flows. Results also show that the model calibration mush be adapted to the DEM used, as both spatial resolution and DEM quality stongly affect results.

In summary, the use of the VORIS 2.0.1. lava-flow model succeeded to replicate the emplacement of the Nyamuragira 2010 lava flow with a degree of accuracy of up to 87 %. Considering that this is a quick, easy-to-use model and one of the few that are freely available on the Internet, it is perfectly adapted for lava flow hazard assessment performed at Goma Volcano Observatory. Additional calibration is however required to adapt simulations to the neighboring Nyragongo volcano, for which the flank eruption style and lava flow propagation are different.

Acknowledgements. Initial results of this work were performed in the framework of a MSc in Natural Risk Management (University of Liège, CUD-2012 Grant. BS was funded by FNR-Luxembourg, through the AFR PhD Grant no. 3221321. J. Marti was funded by the European Commission (FT7 Theme: ENV.2011.1.3.3-1; Grant 282759: "VUELCO"). This study is part of inititiatives lunched in the framework of the GeoRisCA project (Contract no. SD/RI/02A, SSD Research program of the Blegian Science Policy Office).

References

Aoki, K., Yoshida, T., Yusa, K., and Nakamura, Y.: Petrology and geochemistry of the Nyamuragira volcano, Zaire, J. Volcanol. Geoth. Res., 25, 1–28, 1985.

Arefi, H. and Reinartz, P.: Accuracy Enhancement of ASTER Global Digital Elevation Models Using ICESat Data, Remote Sensing, 3, 1323–1343, 2011.

Chakrabarti, R., Basu, A. R., Santo, A. P., Tedesco, D., and Vaselli, O.: Isotopic and geochemical evidence for a heterogeneous mantle plume origin of the Virunga volcanics, Western rift, East African Rift system, Chem. Geol., 259, 273–289, doi:10.1016/j.chemgeo.2008.11.010, 2009.

Crisci, G. M., Di Gregorio, S., Pindaro, O., and Ranieri, G.: Lava flow simulation by a discrete cellular model: first implementation, Int. J. Model. Simul., 6, 137–140, 1986.

Crisci, G. M., Di Francia, A., Di Gregorio, S., Nicoletta, F., Rongo, R., and Spataro, W.: SCIARA-2: A Cellular Automata model for lava flow simulation, in: Proceedings of the Third Annual Conference of the International Association for Math. Geol. IAMG, edited by; Glahn, V. P., 22–27 September 1997, Barcelona, Addendum, 11–16, 1997.

Damiani, M. L., Groppelli, G., Norini, G., Bertino, E., Gigliuto, A., and Nucita, A.: A lava flow simulation model for the development of volcanic hazard maps for Mount Etna (Italy), Comput. Geosci., 32, 512–526, 2006.

d'Oreye, N., Albino, F., Cayol, V., Gonzalez, P., Kervyn, F., Samsonov, S., Smets, B., Wauthier, C., Bagalwa, L. M., Mashagiro, N., Muhindo, A., and Syauswa, M.: Volcano monitoring in the Virunga Volcanic Province, DR Congo, Congrès GeoPrisms, New Jersey, p. 1, 2012.

Favalli, M., Pareschi, M. T., Neri, A., and Isola, I.: Forecasting lava flow paths by a stochastic approach, Geophys. Res. Lett., 32, L03305, doi:10.1029/2004GL021718, 2005.

Felpeto, A., Araña, V., Ortiz, R., Astiz, M., and García, A.: Assessment and modelling of lava flow hazard on Lanzarote (Canary Islands), Nat. Hazards, 23, 247–257, 2001.

Felpeto, A., Martí, J., and Ortiz, R.: Automatic GIS-based system for volcanic hazard assessment, J. Volcanol. Geoth. Res., 166, 106–116, 2007.

Felpeto, A.: VORIS: a GIS-based tool for volcanic hazard assessment, USER'S GUIDE, VORIS 2.0.1, p. 38, available at: http://www.gvb-csic.es (last access: 11 November 2014), 2009.

Hamaguchi, H. and Zana, N.: Introduction to volcanoes Nyiragongo and Nyamuragira, in: Volcanoes Nyiragongo and Nyamuragira: Geophysical Aspects, edited by: Hamaguchi, H., Tohoku University, Sendai, 1–6, 1983.

Head, E. M., Maclean, A. L., and Carn, S. A.: Mapping lava flows from Nyamuragira volcano (1967–2011) with satellite data and automated classification methods, Geomat. Nat. Hazards Risk., 4, 119–144, doi:10.1080/19475705.2012.680503, 2012.

Hormann, C.: Evaluation de la GDEM ensemble de données v2 ASTER, available at: http://www.imagico.de/map/aster_gdem.php, (last access: 28 July 2013), 2012.

Ishihara, K., Iguchi, M., and Kamo, K.: Numerical Simulation of Lava Flows on Some Volcanoes in Japan, in: Lava Flows and Domes, edited by: Fink, J. H., IAVCEI Proceedings in Volcanology, Springer, New York, 174–207, 1989.

Kasahara, M.: Near-field tilt measurements related to the 1981–1982 Nyamuragira eruption, in: Volcanoes Nyiragongo and Nyamuragira: Geophysical Aspects, edited by: Hamaguchi, H., The Faculty of Science, Tohoku University, Sendai, 47–54, 1983.

Kauahikaua, J., Margriter, M., Lockwood, J., and Trusdell, F.: Applications of GIS to the estimation of lava flow hazards on Mauna Loa volcano, Hawaii, in: Mauna Loa Revealed: Structure, Composition, History, and Hazards, Geophys. Monogr., 92, 315–325, 1995.

Komorowski, J. C., Tedesco, D., Kasereka, M., Allard, P., Papale, P., Vaselli, O., Durieux, J., Baxter, P., Halbwachs, M., Akumbe, M., Baluku, B., Briole, P., Ciraba, M., Dupin, J. C., Etoy, O., Garcin, D., Hamaguchi, H., Houlié, N., Kavoyha, K. S., Lemarchand, A., Lockwood, J., Lukaya, N., MAvonga, G., De Michele, M., Mpore, S., Mukambilwa, K., Munyololo, F., Newhall, C., Ruch, J., Yalire, M., and Wafula, M.: The January 2002 flank eruption of Nyiragongo volcano (Democratic Republic of Congo): chronology, evidence for a tectonic rift trigger, and impact of lava flows on the city of Goma, Acta Vulcanol., 27–42, 2003.

Pouclet, A. and Villeneuve, M.: L'éruption du Rugarama (mars–mai 1971) au volcan Nyamuragira (Rep. Zaire), B. Volcanol., 1, 200–221, 1972.

Sheridan, M. F., Hubbard, B., Carasco-Nunez, G., and Siebe, C.: GIS model for volcanic hazard assessment: pyroclastic flow hazard at volcan Citlaltepetl, Mexico, Nat. Hazards, 33, 209–221, 2004.

Smets, B.: Etude des mazukus dans la région de Goma (République Démocratique du Congo) et gestion des risques, ULG, D. E. S. Interuniversitaire en Gestion des Risques Naturels, Année académique, Liège, 2006–2007.

Smets, B., Wauthier, C., and d'Oreye, N.: A new map of the lava flow field of Nyamulagira (DR Congo) from satellite imagery, J. African Earth Sci., 58, 778–786, 2010.

Smets, B., d'Oreye, N., Kervyn, F., Kervyn, M., Albino, F., Arellano, S. R., Bagalwa, M., Balagizi, C., Carn, S. A., Darrah, T. H., Fernández, J., Galle, B., González, P. J., Head, E., Karume, K., Kavotha, D., Lukaya, F., Mashagiro, N., Mavonga, G., Norman, P., Osodundu, E., Pallero, J. L. G., Prieto, J. F., Samsonov, S., Syauswa, M., Tedesco, D., Tiampo, K., Wauthier, C., and Yalire, M. M.: Detailed multidisciplinary monitoring reveals pre- and co-eruptive signals at Nyamulagira volcano (North Kivu, Democratic Republic of Congo), B. Volcanol., 76, 35, 2013.

Smets, B., d'Oreye, N., and Kervyn, F.: Toward Another Lava Lake in the Virunga Volcanic Field?, Eos Trans. Am. Geophys. Union, 95, 377–378, 2014.

Tazieff, H.: An exceptional eruption: Mt. Nyiragongo, 10 January 1977, B. Volcanol., 40, 1–12, 1977.

Tedesco, D.: 1995 Nyiragongo and Nyamulagira activity in the Virunga National Park: A volcanic crisis, Acta Vulcanol., 14–15, 149–155, 2002/2003.

Tedesco, D., Vaselli, O., Papale, P., Carn, S. A., Voltaggio, M., Sawyer, G. M., Durieux, J., Kasereka, M., and Tassi, F.: January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congo, J. Geophys. Res., 112, B09202, doi:10.1029/2006JB004762, 2007.

Verhoogen, J.: Les volcans Virunga et l'éruption du Nyamulagira de 1938, Annales de la société géologique de Belgique, 62, B326–353, 1939.

Wadge, G. and Burt, L.: Stress field control of eruption dynamics at a rift volcano: Nyamuragira, DR Congo, J. Volcanol. Geoth. Res., 207, 1–15, 2011.

Wadge, G., Young, P. A. V., and McKendrick, I. J.: Mapping lava flow hazards using computer simulation, J. Geophys. Res., 99, 489–504, 1994.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Sensibility analysis of length parameter.

Simulation	True lava flow pixels	Simulated pixels	Well estimated pixels	Under estimated pixels	Outside true lava flow pixels	Running time (minutes)	Length parameter (km)	Simulated lava flow longitudinal distance (km)
L1	15 368	477	468	14 900	9	13	1	0.9
L2	15 368	3186	2740	12 628	446	13	5	2.7
L3	15 368	7625	5260	10 108	2365	12	10	5.3
L4	15 368	12 150	7622	7746	4528	13	15	6.9
L5	15 368	16 278	9340	6028	6938	13	20	8.1
L6	15 368	20 875	11 081	4287	9794	14	25	9.4
L7	15 368	26 592	12 478	2890	14 114	14	30	10.3
L8	15 368	34 017	13 349	2019	20 668	13	35	11.6
L9	15 368	40 336	13 806	1562	26 530	13	40	13.4
L10	15 368	49 365	13 959	1409	35 406	13	45	14.3
L11	15 368	57 267	14 078	1290	43 189	14	50	15.4
L12	15 368	64 708	14 119	1249	50 589	15	55	15.9

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 2. Sensibility of "iterations number".

Simulation (number of iterations)	True lava flow pixels	Simulated pixels	Well estimated pixels	Under estimated pixels	Outside true lava flow pixels	Simulated lava flow longitudinal distance (km)	Running time (minutes)
I1 (10)	15 368	3918	2897	12 471	1021	9.6	3
I2 (50)	15 368	8753	6203	9165	2550	10.9	3
I3 (100)	15 368	12 227	7777	7591	4450	10.4	3
I4 (500)	15 368	20 054	10 725	4643	9329	11.6	4
I5 (1000)	15 368	23 455	11 610	3758	11 845	11.1	4
I6 (5000)	15 368	30 808	13 136	2232	17 672	11.6	14
I7 (10 000)	15 368	29 671	12 904	2464	16 767	11.8	23
I8 (50 000)	15 368	31 125	13 202	2166	17 923	11.1	110
I9 (100 000)	15 368	30 981	13 215	2153	17 766	11.3	228
I10 (500 000)	15 368	31 125	13 227	2141	17 898	11.1	700

Table 3. Sensibility analysis of lava flow average thickness.

Simulation (lava flow average thickness in m)	True lava flow pixels	Simulated pixels	Well estimated pixels	Under estimated pixels	Outside true lava flow pixels	Running time (min)	Simulated lava flow longitudinal distance (km)
h1 (1 m)	15 368	4465	3511	11 857	954	14	7.6
h2 (2 m)	15 368	30 449	11 719	3649	18 730	13	14.2
h3 (3 m)	15 368	31 503	13 130	2238	18 373	15	11.6
h4 (4 m)	15 368	27 442	12 601	2767	14 841	14	9.8
h5 (5 m)	15 368	27 199	12 095	3273	15 104	14	8.8
h6 (6 m)	15 368	24 782	11 536	3832	13 246	15	8.2
h7 (7 m)	15 368	23 470	10 685	4683	12 785	14	7.1
h8 (8 m)	15 368	23 337	10 470	4898	12 867	15	7.1

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 4. Sensibility analysis of DEM parameter.

Simulation	Simulated pixels	True lava flow pixels	Under estimated pixels	Outside true lava flow pixels	Running time (min)	Simulated surface km^2	Well-estimated surface km^2	Under estimated surface km^2	Over estimated surface km^2
S1	31 402	13 094	2274	18 308	14	0.9421	0.39282	0.06822	0.54924
S2	17 652	1690	45	15 962	9	1.5887	0.1521	0.00405	1.43658
S3	704	476	15 821	228	16	0.0211	0.01428	0.47463	0.00684

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

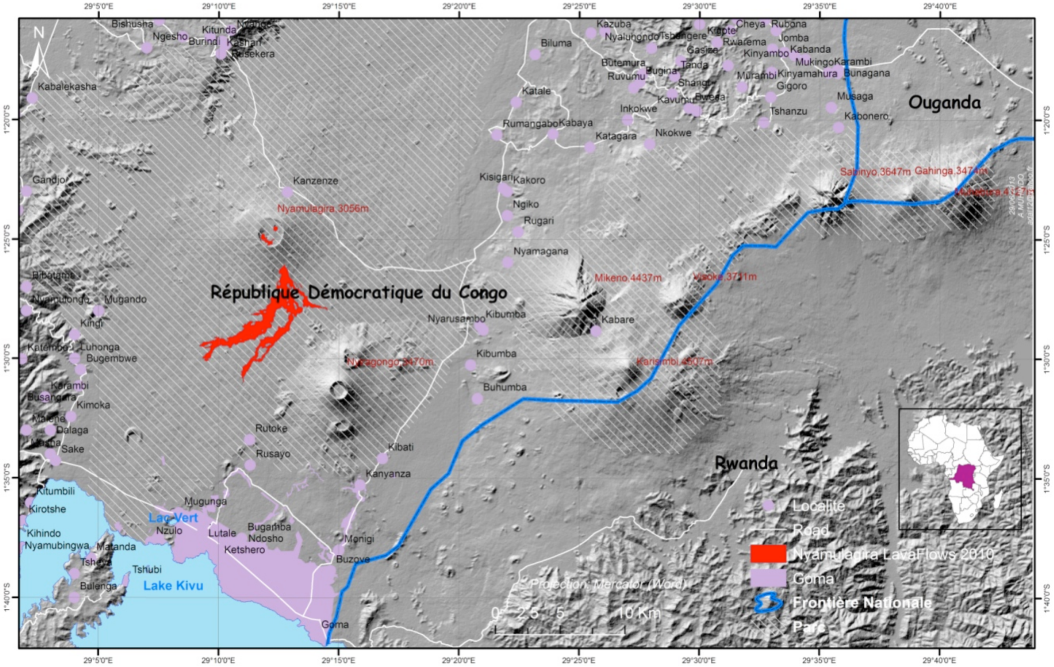

Figure 1. Location of the Virunga region with the Nyamulagira volcano and 2010 lava flows indicated in red.

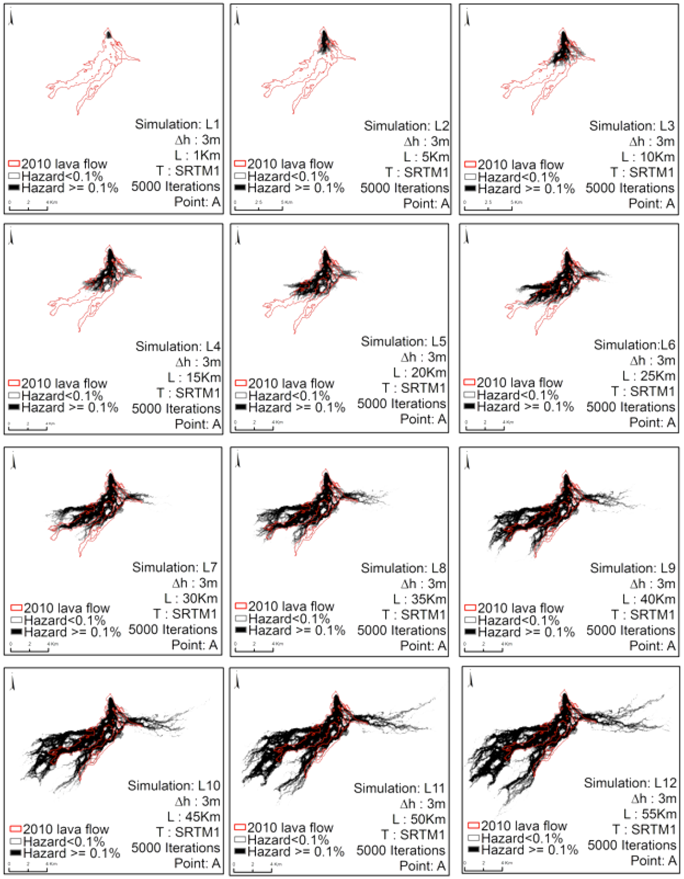

Figure 2. Probability of invasion of lava flows from the point of emission A for various parameter lengths (L1–12).

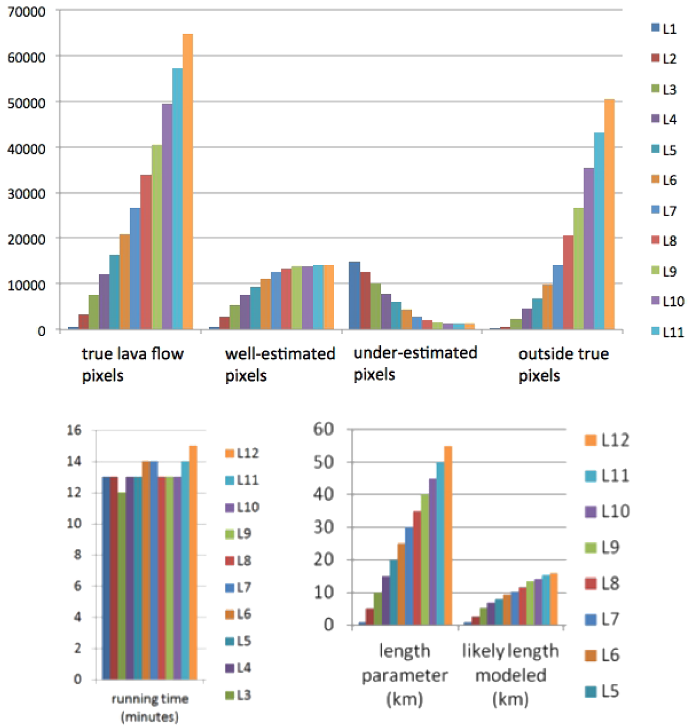

Figure 3. Sensibilities of length parameter. (From L1–12 simulations of 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 55 km length, respectively).

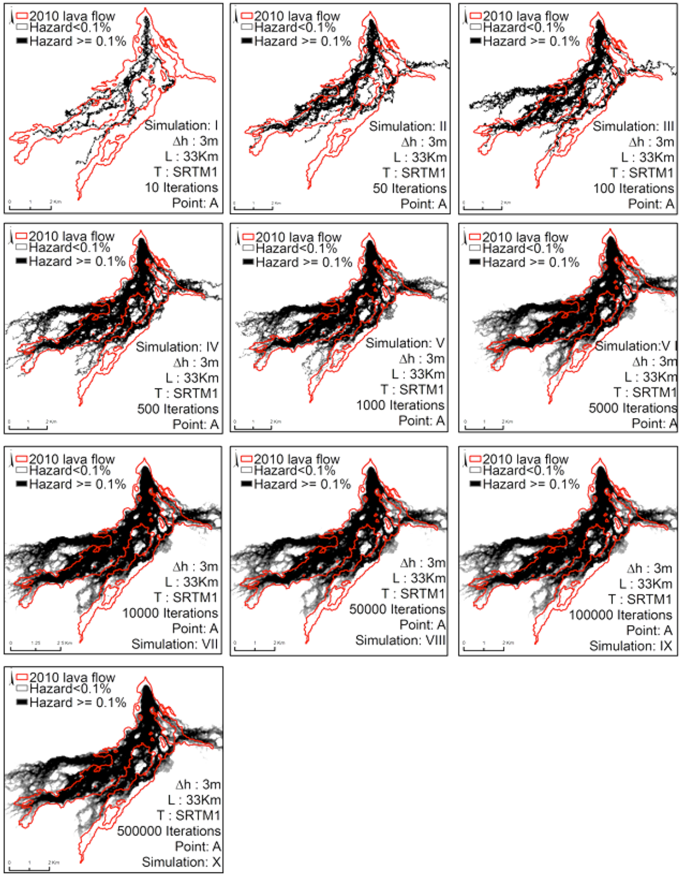

Figure 4. Simulations considering 10, 50, 100, 500, 1000, 5000, 10 000, 50 000, 100 000, and 500 000 iterations.

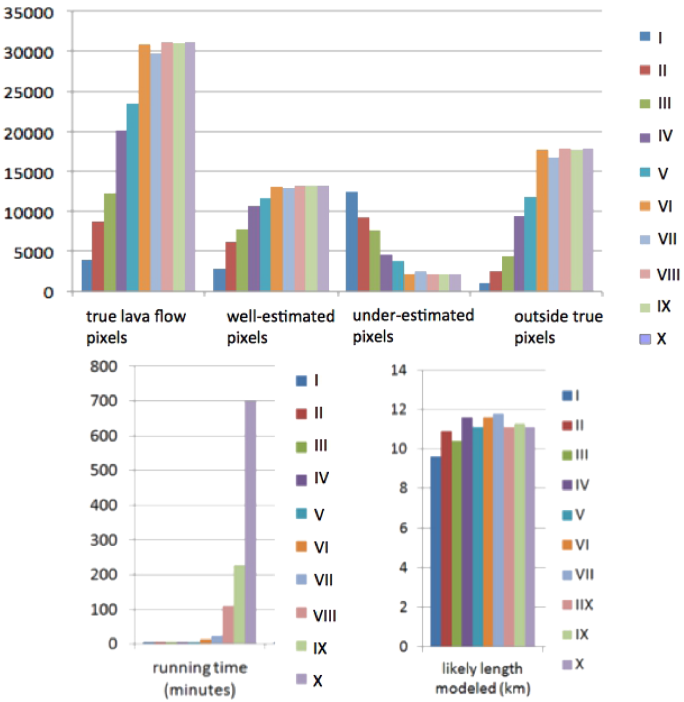

Figure 5. Sensibilities of the parameter "iterations number". (I to X simulations: 10, 50, 100, 500, 1000, 5000, 10 000, 50 000, 100 000, and 500 000 iterations, respectively.)

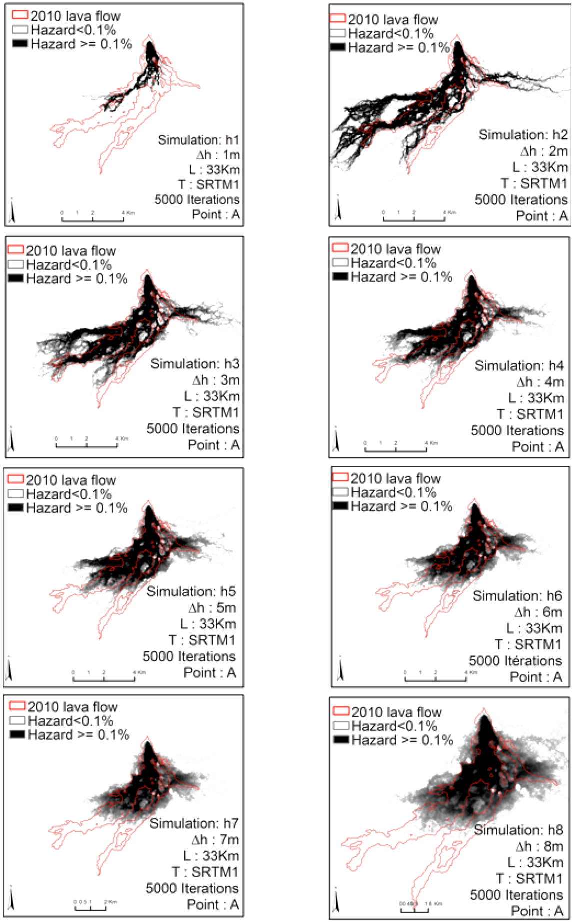

Figure 6. Simulations considering different values of height correction (Δh) (average lava flow thickness).

NHESSD
3, 1835–1860, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

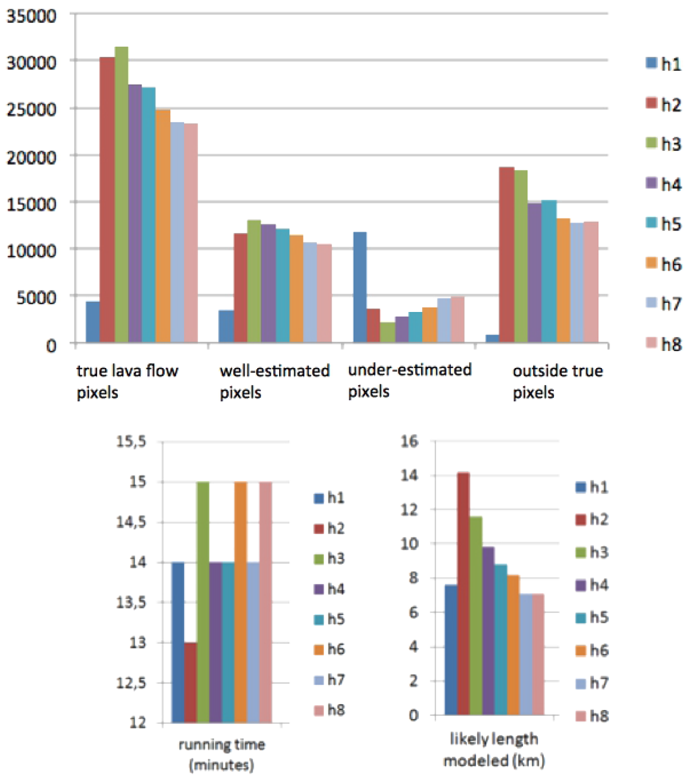

Figure 7. Sensibilities of the parameter "thickness of the lava flow". (h1–h8, simulations of 1, 2, 3, 4, 5, 6, 7 and 8 m of lava-flow thickness, respectively.)

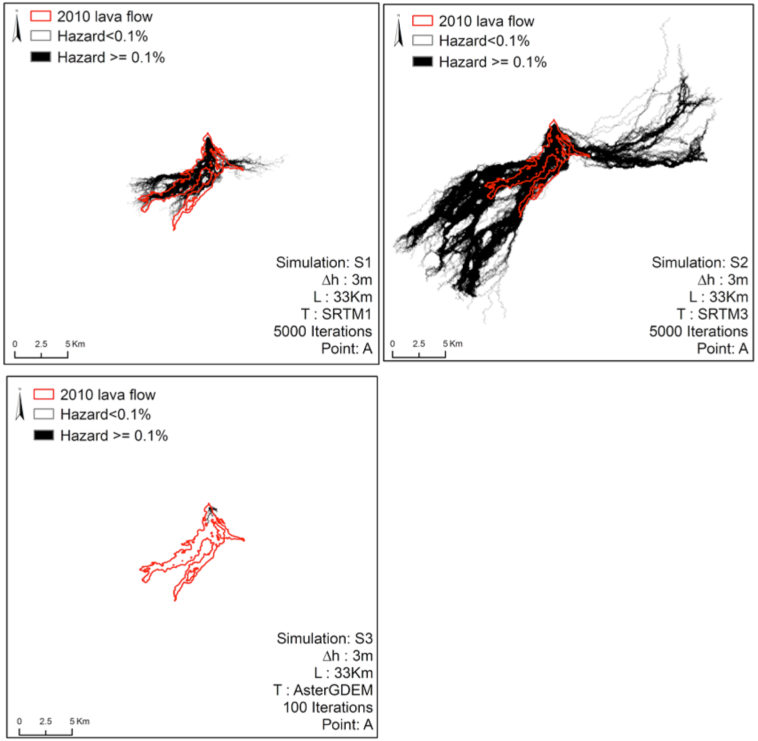

Figure 8. Probability of invasion of lava flows from A (point emission) for different DEMs (S1, S2, and S3).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

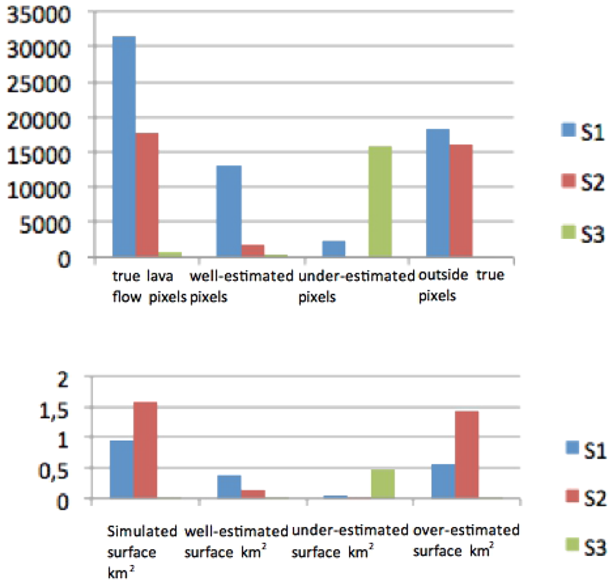

Figure 9. Sensibilities of DEM parameter (S1, S2, and S3 simulations corresponding, respectively, to SRTM1, SRTM3, and ASTER GDM).