Q-LAVHA: A flexible GIS plugin to simulate lava flows

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ABSTRACT

Q-LavHA is a freeware plugin which simulates lava flow inundation probability from one or regularly distributed eruptive vents on a Digital Elevation Model (DEM). It combines existing probabilistic and deterministic models and proposes some improvements to calculate the probability of lava flow spatial propagation and terminal length. Spatial propagation is constrained by the probabilistic steepest slope. Corrective factors are included to allow the flow simulation to overcome small topographical obstacles and to fill pits. The terminal length of the flow simulation can be determined based on a fixed length value, a statistical length probability function or based on the thermo-rheological properties of an open-channel lava flow. The impact of model parameters, background slope and DEM resolution on the accuracy of the simulations are discussed. The user-friendly interface and the flexibility of Q-LavHA makes it a tool applicable from long-term volcanic hazard assessment to short-term hazard forecasting.

1. Introduction

Accurate simulation of lava flow extent is essential information for scientists or stakeholders confronted with imminent or long-term lava flow hazard from basaltic volcanoes. Knowing what can be the area inundated by a potential or imminent lava flow can improve their understanding of the spatial distribution of lava flow hazard, influence their land use decisions and support evacuation planning during a volcanic crisis (Herault et al., 2009; McGuire et al., 2009; Morgan et al., 2013).

Since the 1980’s, lava flow models have been proposed to address the problem of lava flow emplacement. Commonly, lava flow emplacement in these models is constrained by the topography. Models extract from a DEM the elevation of the pixels surrounding the lava. Based on defined rules, the models pick one or several surrounding pixels where lava can propagate (e.g. Young and Wadge, 1990; Felpeto et al., 2001; Connor et al., 2012).

Existing models differ in the way the maximum length reached by the lava flow is computed. The most straightforward way of modelling lava flow termination is to simulate it till a maximum length has been reached (Damiani et al., 2006; Felpeto et al., 2001; Tarquini and Favalli, 2013). Bonne et al., (2008) propose to calibrate lava flow length with a decreasing cumulative function. This takes into account that the probability a site will suffer from lava flow inundation is inversely related to the distance between the site and the location where the opening of an eruptive vent is possible. Tarquini and Favalli (2013) suggest that a lava flow has a uniform probability of attaining a specific length defined by the vent elevation. When reaching that length, the probability decreases linearly to zero. More realistic conditions to stop a lava flow are controlled by physical properties of the lava assuming that its terminal length depends on a limited lava volume (Connor et al., 2012; Young and Wadge, 1990) or is controlled by cooling (e.g. Harris and Rowland, 2001; Hidaka et al., 2005; Vicari et al., 2007).

Assuming a specific emitted lava volume, the former models simulate lava flow over the DEM leaving behind a certain lava thickness at each cell. When the remaining volume is no longer sufficient to propagate, lava flow stops (Connor et al., 2012; Harris, 2013; Young and Wadge, 1990). The cooling-limited models use physical equations in order to
compute the heat losses, over time and distance, incurred by the lava. This allows estimating the lava cooling and the crystallization rate which affect the rheological properties of the lava. Lava flow is maintained until the cooling of the lava induces a too low velocity, and a too high viscosity and yield strength which force the lava flow to stop (Crisci et al., 2004; Harris, 2013; Miyamoto and Sasaki, 1997; Vicari et al., 2007). Physically-based volume- and cooling-limited models produce detailed outputs, providing information per pixel such as lava flow thickness and temperature. Drawback is that they require a large amount of input parameters.

The lava flow lateral extension can be modelled by a probabilistic approach using multiple flow path iterations or by cellular automata (Damiani et al., 2006; Felpeto et al., 2007; Harris, 2013). The difference between both models is that the former do not look at the flow dynamics and the output expresses the probability of a pixel to be inundated. In lava probabilistic approaches, topography plays an important role in lava flow emplacement and dealing with the filling of topographical depressions and the expansion of lava over flat areas is important. Filling abnormal depressions during a pre-processing manipulation can avoid the simulation to be stuck due to errors present in the DEM (Favalli et al., 2005). Favalli et al. (2005) also stochastically perturbate the topography after each iteration. Other models add a corrective elevation factor to simulate lava flow thickness which is constant or varies with lava flow length (Damiani et al., 2006; Felpeto et al., 2001).

While the models mentioned above have demonstrated their capacity to accurately predict lava flow extent based on test cases, each existing model has its particular strengths and restrictions. Although for some models code is available online or upon personal request, most models are not easily available to the public.

This paper presents a lava flow simulation tool for channelized ‘a‘a flows running in the open source Geographical Information System (GIS) software QGIS. Q-LavHA (Quantum-Lava Hazard Assessment) combines several existing models which allows the users to select the most appropriate method, based on available data and knowledge about the lava flows to be modelled. The plugin also proposes improvements of these models.

In order to assess the quality of lava flow simulations with Q-LavHA, a sensitivity analysis of key input parameters is conducted. Lava flows with different slope profiles have been selected on Mount Etna (Italy) and Nyamuragira volcano (D.R.Congo). Q-LavHA is also tested on different DEM spatial resolutions.

2. Model concepts

Q-LavHA enables the user to combine different models that determine the spatial propagation of a channelized ‘a‘a lava and its terminal length on a DEM using an iterative approach. Based on the user’s choices, it computes, for one or regularly distributed vents, a predefined number of lava flow lines (iterations) which are then combined based on the activated simulation parameters (Eq. 11) in order to express the pixel probability to be inundated by lava. Fitness indices can be calculated.

2.1. Eruption sources

The eruption source(s) can be defined in Q-LavHA as a point, a line or a surface area. The first two allow the user to simulate a lava flow issued from a well-defined vent or an eruptive fissure respectively. Surface area enables to simulate multiple eruption scenarios from a probable eruption area. With line or surface simulations, eruption occurs at regular spatial intervals according to a user-defined vent spacing. Susceptibility maps can be used to weight the probability of occurrence of different vent locations ($p_{uv,v}$) and therefore produce hazard maps (Bartolini et al., 2013; Felpeto et al., 2001; Tarquini and Favalli, 2013) (Eq. 11). Here we demonstrate the applicability of Q-

![Fig. 1. Schematic representation of the central pixel and its surrounding pixels. The lava flow path evolves on the elevation pixels of the DEM and analyses progressively the surrounding pixels of the central pixel which the lava flow reached. Lava propagates through the DEM from one source pixel to one of its eight surrounding pixels (Fig. 1). To determine the next pixel along the lava flow path, a flow probability ($P$) is calculated for each of the eight pixels surrounding the central pixel reached by the flow line:](image)

$$P_i = \frac{\Delta h_i}{\sum_{j=1}^{8} \Delta h_j}, \quad i = 1, 2, 3, \ldots, 8$$

where $\Delta h_i$ represents the difference in altitude between the central pixel ($i = 0$) and each of the eight surrounding pixels ($i = 1, 2, \ldots, 8$). If the difference between the pixel where the lava is localized and the surrounding pixel is negative, $\Delta h_i$ is put to zero since the propagation of lava uphill is impossible. Backward propagation on a pixel where the flow has originated from is not allowed. In this case, $\Delta h_i$ is also put to zero.

Corrective factors are included enabling the lava to overcome small topographical obstacles or pits (Fig. 2). The factor $H_i$ (m) is always added to the elevation of the central pixel before calculating $\Delta h$ (Eqs. 2 and 3). This enables to represent the lava thickness (Felpeto et al., 2001). As it is observed that real lava flows are capable of flooding pre-existing depressions (Sigurdsson et al., 2015) whereas lava flow lines would be trapped numerically into the topographic depression, we propose the introduction of a higher corrective factor, $H$ (m), which can be applied if the source pixel is surrounded by eight pixels at a higher elevation pixels which $H_i$ cannot overcome (Fig. 2). This simulates the ability of lava to fill pits and pursue its flow (Eqs. 4 and 5).

$$\text{If } (h_0 + H_i) - h_i \geq 0 \text{ then } \Delta h_i = (h_0 + H_i) - h_i \quad (2)$$

$$\text{If } (h_0 + H_i) - h_i < 0 \text{ then } \Delta h_i = 0 \quad (3)$$

If all $\Delta h_i = 0$ then

$$\text{If } (h_0 + H_i) - h_i \geq 0 \text{ then } \Delta h_i = (h_0 + H_i) - h_i \quad (4)$$

$$\text{If } (h_0 + H_i) - h_i < 0 \text{ then } \Delta h_i = 0 \quad (5)$$

Where $h_0$ represents the elevation of the central pixel and $h_i$ the elevation of the analyzed pixel, both expressed in m.

All corrective factors included in Q-LavHA are temporally added to the DEM for calculation purposes. Therefore, these factors do not
permanently modify the DEM and do not affect flow simulation for other pixels along the flow line or other lava flow line simulations.

After calculating a probability \( P \) for each of the eight pixels surrounding the central pixel, a cumulative probability value \( S_i \) is calculated for each pixel, depending on its index value (Eq. 6), and a random number \( (\text{rnd}) \) is drawn between zero, included, and one, excluded. If the random number falls within the interval \([S_{i-1} \leq S_i] \), pixel \( i \) is selected as the next pixel on the lava flow path (Felpeto et al., 2001) (Eq. 7):

\[
S_i = \sum_{j=1}^{i} P_j, \quad i = 1, 2, \ldots, 8
\]

(6)

where \( S_i \) is the cumulative probability attributed to the pixel with index value \( i \) and \( S_0 \) equals zero.

\[
S_{i-1} \leq \text{rnd} < S_i, \quad i = 1, 2, \ldots, 8
\]

(7)

Q-LavHA includes the possibility to calculate the probability according to Eq. (8) instead of Eq. 1, using the second power of \( \Delta h \) for computing the probability of propagation. This implies that pixels with higher elevation differences obtain higher probabilities. Therefore, the flow line is more likely to follow the steepest slope path.

\[
P_i^2 = \frac{(\Delta h_i)^2}{\sum_{j=1}^{n} (\Delta h_j)^2}, \quad i = 1, 2, \ldots, 8
\]

(8)

If the lava line reaches a pit, which is too deep to be overcome by the corrective factors \( H_c \) and \( H_p \), Q-LavHA includes the option to consider the 16 next surrounding pixels (Fig. 1). If one of these 16 pixels meets the requirement expressed by Eqs. (2) or (4) then the lava flow line propagates to the pixel picked by the \( \text{rnd} \) and continues its path. If not, the simulation stops.

2.3. Lava flow length constraints

Lava emplacement is controlled by a complex interplay between mainly the effusion rate, underlying topography, lava viscosity, yield strength, cooling processes, morphology and propagation dynamics (Harris and Rowland, 2001; Proietti et al., 2009). However, many of these parameters are often not available or poorly constrained for a specific lava flow, they are difficult to predict and they vary between eruptions (Damiani et al., 2006). To enable short-term forecasting, alternatives have to be found. In this context, Q-LavHA proposes three alternatives to terminate a flow line.

The first option is to define a maximum length till where the lava can flow \( (L_{\text{max}}) \). This distance can be estimated by studying the maximum length reached by historical lava flows of the studied volcano. At each step in the lava flow path simulation, the distance covered by the lava flow line is calculated. When the lava flow line reaches the maximum length defined by the user, the iteration stops.

Because the length of each lava flow is not constant for a given volcano, it can be assumed that the probability of reaching a certain length can be expressed by a decreasing cumulative density function following a normal distribution \( \phi \) (Bonne et al., 2008) \( (L_{\text{normal}}) \). In a second option, Q-LavHA therefore allows weighting the probability of lava inundation of each pixel along a lava flow line based on Eq. (9):

\[
\phi(x, \mu, \sigma) = 1 - \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x - \mu}{\sqrt{2}\sigma} \right) \right]
\]

(9)

where \( x \) represents the distance from the source along the flow line, \( \mu \) represents the average length and \( \sigma \) the standard deviation of the historical lava flows. The flow line is simulated until reaching a distance equal to \( \mu+3\sigma \) at which point the weighting factor \( \phi \) is equal to 0.15%.

The last option to define the lava flow line length is based on the one-dimensional FLOWGO cooling-limited model (Harris and Rowland, 2001) \( (L_{\text{flowgo}}) \). Because lava in an open channel loses heat...
while flowing downslope, the rheological properties of the lava change. At each step along the flow line, thermal, rheological and dynamic parameters are adapted based on the slope encountered in order to calculate the evolution with distance of the dependent variables. The lava flow stops when at least one of the following conditions holds: its velocity is zero, the lava core temperature reaches the solidus or the yield strength at the base of the channel is greater than the downhill stress. FLOWGO assumes a constant lava channel depth and calibrates the channel width and flow velocity to maintain a constant discharge. Attention has to be given to the fact that simulations are done based on the FLOWGO model using a few simplifications: heat loss by rain vaporization and heat gain from viscous dissipation are neglected; the crystallization is considered a linear function of the cooling (Harris and Rowland, 2001).

2.4. Lava inundation probability

The result obtained after simulation is an integration of all the lava flow lines computed from one or multiple eruptive vents. The number of lava flow lines computed from one vent is defined by the number of iterations that has been specified in Q-LavHA.

After each iteration, an incremental probability to be inundated \( p_{\text{inund}} \) is attributed to each pixel that is part of the obtained flow line corresponding to one over the total number of iteration (Eq. 10). This probability is added up to the matrix which allows, defining the final pixel probability to be inundated \( \text{PROB} \). Q-LavHA can generate simulation for line or areal eruption source, representative of fissure eruptions and clusters of closely spaced vents respectively. In this case, all simulations are then combined and divided by the total number of vents simulated (Eq. 11).

\[
\text{prob}_{\text{i}} = \frac{1}{(\text{total number of iterations})} \\
\text{PROB}_{\text{i}} = \frac{\sum \text{prob}_{\text{i}}}{\text{number of vents simulated}} \times \varphi \times \varphi_{\text{inund}} \\
\]  

(10)

(11)

In the case of a simulation where a decreasing cumulative density function is used for constraining the length of the flow path, pixel probabilities are weighted with the probability of reaching a certain length \( (\varphi) \) (Eq. 11). If a susceptibility map is used they are weighted with the probability of occurrence of the vent location from which the flow line is starting \( (\varphi_{\text{inund}}) \) (Eq. 11). If both options are activated, these parameters can be combined. If none of the two options is used, \( \varphi \) and \( \varphi_{\text{inund}} \) are kept to one.

In the outcome of the simulation, each pixel is characterized by the probability of being inundated by lava. A threshold can be defined in order to keep only those pixels having probabilities higher than a certain value. Probabilities below that threshold, i.e. pixels that are flooded by a limited number of flow lines, are then considered as noise and are neglected.

2.5. Fitness index

To assess the accuracy of the simulated lava flow, a fitness index \( (F_1) \) can be calculated. This index compares the simulated lava flow to a real lava flow (Fig. 3) (Favalli et al. (2009)). The overlapping area \( (Fl_{\text{true positive}}) \) between the real flow and the simulated lava flow is divided by the total area covered by the two flows (Eq. 12):

\[
Fl_{\text{true positive}} = \frac{A_r \cap A_s}{A_r \cup A_s} \\
\]  

(12)

where \( A_r \) represents the area covered by the simulated lava flow and \( A_s \) is the area covered by the real lava flow. The \( F_1 \) varies between zero and one. The closer \( F_1 \) gets to one, the more important is the overlap and the better the simulated lava flow corresponds to the real lava flow.

However, for properly interpreting the result of the simulation and for effective use in risk management, it is important to assess if the mismatch between the simulated flow and real flow is mostly due to an overestimation \( (Fl_{\text{false positive}}) \) or underestimation \( (Fl_{\text{false negative}}) \) of the inundated area by the simulation (Fig. 3):

\[
Fl_{\text{false positive}} = \frac{A_f - (A_r \cap A_s)}{A_r \cup A_s} \\
Fl_{\text{false negative}} = \frac{A_f - (A_r \cap A_s)}{A_r \cup A_s} \\
\]  

(13)

(14)

The values of the three indexes, for which the sum is equal to one, can be used to optimize the set of input parameters chosen to reproduce a lava flow. Based on the precautionary principle in a context of hazard assessment, we consider it less problematic to overestimate the future inundated area rather than to underestimate it. It is expected that if Q-LavHA is well-calibrated for several past flows of a given volcano with a homogenous lava type and topography, the model will accurately simulate future lava paths.

2.6. QGIS plugin

Q-LavHA is a plugin for QGIS, a free, open-source and cross-platform geographic information system, distributed through www.qgis.org. The plugin can be downloaded from the websites http://we.vub.ac.be/en/q-lavha or http://www.vetools.eu/results/. After installation, the plugin is available from the QGIS toolbar or plugin menu. Q-LavHA has a graphical user interface divided in three sections where the user can define the input and output parameters, the vent type and location and the simulation parameters. This facilitates its distribution and use by the community. A manual on how to use Q-LavHA is provided on the website as well as a reference data set.

3. Case studies

To illustrate the functionality of Q-LavHA, two distinct lava flows have been selected. The well documented 2001 Etna lava flow has been repetitively modelled over time (Crisci et al., 2004; Vicari et al., 2007; Proietti et al., 2009; Tarquini and Favalli 2011). This allows a good parametrization of Q-LavHA. To evaluate the accuracy of simulations produced by Q-LavHA for less well documented lava flows, the 2006 Nyamuragira lava flow has been selected. All parameters extracted from the literature to simulate both lava flows in Q-LavHA are listed in Tables 2 and 3.

The 2001 ’a‘ā lava flow on Mount Etna (Italy) propagated from the Lower Fissure System 1 close to Mount Calcarrazion steep slopes (Coltelli et al., 2007) (Table 1). To analyze the lava flow on Mount Etna, a 10 m resolution DEM (TINITALY/01) has been used (Tarquini et al., 2012). In this area, the DEM has a root mean square error in elevation (RMSEz) of 1.98 m. The 10 m resolution DEM has been aggregated to produce a 30 and 90 m resolution DEM.

The 2006 ’a‘ā lava flow on Nyamuragira volcano (D.R.Congo) erupted from a vent at the base of its Southeastern flank and propagated on gentle slopes (Simets et al., 2015) (Table 1). Our measurements of historical lava flow lengths on Nyamuragira yield a mean of 14.2 km with a standard deviation of 5.7 km. The Nyamuragira flow is analyzed thanks to a TanDEM-X DEM (2011) of 5 m resolution aggregated to 30 m and a SRTM DEM (2000) of 30 and 90 m resolution. The relative vertical accuracies of these DEMs are 1 m (Albino et al., 2015) and 10 m (NASA, 2005), respectively.

4. Results and discussion

4.1. Impact of model parameters

Without topographic corrective factors, simulations may be constrained by depressions and may not reach the maximum length defined by the user because they quickly arrive in pits which cannot
and the simulated lava indicates a good fit, the $F_{\text{false positive}}$, an overestimation and the $F_{\text{false negative}}$, an underestimation of the real lava flow.

![Fig. 3. Schematic representation of fitness indexes calculations.](Image)

**Table 1.** Lava flows characteristics.

<table>
<thead>
<tr>
<th></th>
<th>2001 Etna</th>
<th>2006 Nyamuragira</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start date</td>
<td>18th of July 2001</td>
<td>27th of November 2006</td>
</tr>
<tr>
<td>Stop date</td>
<td>9th of August 2001</td>
<td>11th of December 2006</td>
</tr>
<tr>
<td>Slope</td>
<td>8.71°</td>
<td>2.55°</td>
</tr>
<tr>
<td>Lava type</td>
<td>‘a’</td>
<td>‘a’</td>
</tr>
<tr>
<td>Peak effusion rate</td>
<td>30.68 m$^3$/s$^c$</td>
<td>155 ± 78 m$^3$/s$^d$</td>
</tr>
<tr>
<td>Volume</td>
<td>21.40x10$^6$ m$^3$</td>
<td>46.29 ± 3.39 m$^3$</td>
</tr>
<tr>
<td>Length</td>
<td>6.4 km$^g$</td>
<td>13.3 km$^g$</td>
</tr>
<tr>
<td>Maximum width</td>
<td>545 m</td>
<td>1.2 km</td>
</tr>
<tr>
<td>Minimum lava flow thickness</td>
<td>3.2 m</td>
<td>0.5 m$^c$</td>
</tr>
<tr>
<td>Maximum lava flow thickness</td>
<td>5 m</td>
<td>10 m$^c$</td>
</tr>
</tbody>
</table>

$^a$ (Coltelli et al., 2007).
$^b$ (Smets et al., 2015).
$^c$ The effusion rate has been evaluated by dividing partial volume by time span.
$^e$ Standard deviation of the volume is of 0.37x10$^6$ m$^3$.
$^f$ In azimuth.
$^g$ (Pouclet, 1976).

be overcome (Fig. 4a). Therefore, the use of corrective factors is important. When applying the $H_e$ correction, the lava flow propagates laterally (Fig. 4b). This implies that maximum inundation probability values observed in the flow are lower than without the $H_e$ correction due to the diversity of possible paths. Moreover, the crown flies distance reached by the lava flow is shorter than the distance defined by the user due to the complexity of the paths. Outcomes with $H_e$ (Fig. 4c) differ from the previous ones. Because this parameter is only used if the elevation of the central pixel does not enable the lava flow to pursue its course, the lateral lava flow propagation is limited. This is why, maximum probabilities in the main channel are higher than with $H_e$ and the length reached by the simulation is closer to the length as defined by the user. When combining both corrective factors the lateral propagation is still present, but the flow is more constrained (Fig. 4d). Because $H_p$ is first applied, it has a bigger impact on the outcome. The $H_p$ value needs to be larger than $H_e$ to be effective.

An optimal $H_p$ is defined by a high $F_{\text{true positive}}$ and $F_{\text{false positive}}$ and a low $F_{\text{false negative}}$. Looking at the results obtained for the 2001 Etna lava flow using a 30 m resolution DEM (Fig. 5), the optimal $H_p$ value is 2 m. This value is close to the minimum thickness observed for this flow (3.2 m, Coltelli et al., 2007).

The influence of $H_p$ on the obtained $F_i$ values is less clear because compared to $H_e$ its impact on the outcome of the simulation is more limited. However, its use especially on gentle slopes is of great importance (Fig. 6). Under this circumstance, $H_p$ is more frequently used, and allows the model to deal with DEM errors or topographical obstacles that $H_e$ cannot correct for.

Squaring elevation differences reduces the width of the lava flow (Fig. 4e–h). The flows become more concentrated and pixel inundation probabilities reach higher values in the main channels. The $F_is$ indicate (Fig. 7) that the use of squared elevation differences (Eq. 8) in the calculation of flow line probabilities improves the simulation especially for steep slopes. The probability that the lava flow will follow the steepest slope is increased and simulations show a better fit with the real lava flow.

As Q-LavHA uses a probabilistic approaches, it is important that sufficient iterations are run for each simulation. Too few iterations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Etna</th>
<th>30 m</th>
<th>10 m</th>
<th>Nyamuragira</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM resolution</td>
<td>90 m</td>
<td>30 m</td>
<td>10 m</td>
<td>90 m</td>
</tr>
<tr>
<td>Vent of eruption</td>
<td>(500506; 4173306)</td>
<td>(500506; 4173306)</td>
<td>(500506; 4173306)</td>
<td>(745898; 9837912)</td>
</tr>
<tr>
<td>Number of iteration</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>$H_e$</td>
<td>3.2 m</td>
<td>3.2 m</td>
<td>3.2 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>$H_p$</td>
<td>16.5 m$^d$</td>
<td>16.5 m$^d$</td>
<td>16.5 m$^d$</td>
<td>10 m$^d$</td>
</tr>
<tr>
<td>$p_i^2$</td>
<td>Activated</td>
<td>Activated</td>
<td>Activated</td>
<td>Activated</td>
</tr>
<tr>
<td>Threshold</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$F_{\text{true positive}}$</td>
<td>0.15</td>
<td>0.37</td>
<td>0.39</td>
<td>0.23</td>
</tr>
<tr>
<td>$F_{\text{false positive}}$</td>
<td>0.85</td>
<td>0.57</td>
<td>0.41</td>
<td>0.63</td>
</tr>
<tr>
<td>$F_{\text{false negative}}$</td>
<td>0</td>
<td>0.06</td>
<td>0.20</td>
<td>0.04</td>
</tr>
</tbody>
</table>

$^a$ real length of the channel.
$^b$ (Coltelli et al., 2007).
$^c$ (Pouclet, 1976).
produces results not representative of the real lava inundation probability and the flow spatial propagation (Fig. 8a left). Another consequence is that the \textit{F}_{\text{true positive}} will remain low (Fig. 8b). Too many iterations increases computational time. The time needed for Q-LavHA to simulate a lava flow on a 30 m DEM resolution increases linearly with the amount of iterations (Fig. 8c). A proper balance thus has to be found regarding the number of iterations needed. In contrast to models such as DOWNFLOW which need a large number of iterations to obtain a good fit between simulations and real flow (Favalli et al., 2005), the observations with Q-LavHA show that simulation outcomes stabilize around 1500 iterations on average (Fig. 8b). Therefore, 1500 iterations can be considered as a good compromise between obtaining a good estimate of lava flow extension and computation time (Fig. 8a).

From our observations both on the Etna and Nyamuragira flows, the highest probabilities are located in the main channel of the real lava flow (Fig. 8a right). However, most of the pixel probabilities corresponding to the real flows do not reach high values. This is due to the random character of the model and the corrective topographic parameters included in Q-LavHA, which simulate the capability of lava flows to propagate in different directions other than the steepest slope. Therefore, the flows do not take the same direction at each iteration.

To avoid that too small probabilities are included in the simulated lava flow, a threshold can be defined so that pixels which are inundated by a very small fraction of the lava flow lines are not considered in the final simulation output. The value chosen for the threshold is best defined based on simulations for which the extent of the real lava flow is available. When using a 30 m resolution DEM a low threshold (~0–1%) should hence be defined (Fig. 9). This is because a low to zero threshold will increase the false positive area, but will maximize the true positive area, which might be preferential to support evacuations.

### 4.2. Lava flow length constraints

Q-LavHA proposes three alternatives to terminate a flow line. The selection of one of them depends on the available data, the user’s knowledge or decision on how to account for uncertainties.

The maximum length of the channelized ‘a‘ā lava flow \( L_{\text{max}} \) is an approach which is easy, fast and to be recommended to users who want to calibrate the model when little knowledge on lava flow properties is available. Using this approach, simulation of the 2001 Etna lava flow (Fig. 10a) indicates that the highest probabilities are observed in the main channel of the flow and that the pattern of the flow is well

![Fig. 4. Illustration of the impact of the topographic corrective factors on the simulations of a hypothetical eruption vent on a gentle slope topography (~3°). The squared elevation differences in the calculation to determine the next pixel along the lava flow path (Eq. 8) can be activated or not (square off-square on). This influences the spatial propagation of the simulated lava flow. The DEM resolution used to simulate these imaginary lava flows is 90 m.](image-url)

![Fig. 5. (a) Evolution of the fitness indexes of the 2001 Etna lava flow on a 30 m DEM resolution for different \( H_c \) values. The best \( F_{\text{true positive}} \) is obtained when \( H_c = 2 m \). The parameters used in these simulations are the standard ones defined in Table 2 (\( H_p = 0 m; L_{\text{max}} = 8.442 m \)). (b) Illustration of the simulation obtained when using the optimum \( H_c \). The parameters used in these simulations are the standard ones defined in Table 2 (\( H_c = 2 m; H_p = 0 m; L_{\text{max}} = 8.442 m \)).](image-url)
Low probabilities are observed South-East of the eruption vent and the lateral eastern branch is less well simulated by Q-LavHA because it has been produced by ephemeral vents that opened near Mt. Gemellaro at the end of the eruption. Taking the length reached by the historical lava flow (6.700 m) as the $L_{\text{max}}$ value does not allow simulating the flow until the real lava flow front (Fig. 10a). This is partly due to the fact that each flow line follows an irregular trajectory whose length is longer than the shortest distance along the main lava flow channel. Similar observations are made when simulating on more gentle slopes.

Weighting the pixel probability based on the probability of the channelized ‘a’a lava flow of reaching a certain length ($L_{\text{normal}}$) is applicable when limited knowledge of previous lava flows is available and improves the predictability of potential future lava flows of

Fig. 6. Visual representation of the use of $H_c$, $H_p$ and the 16 next surrounding pixels option ($H_A$) on gentle (Nyamuragira, slope = 2.55°, $L_{\text{max}}$ =19.551 m) and steep (Etna, slope = 8.71°, $L_{\text{max}}$=8.442 m) slopes using 30 m DEM resolution. The parameters used in these simulations are the standard ones defined in Table 2.

Fig. 7. (a) Influence on the 2001 Etna lava flow simulations of the $P_I^{2}$ when activated or not. The parameters used in these simulations are the standard ones defined in Table 2 ($L_{\text{max}}$=8.442 m). (b) Evolution of the $F_{I_{\text{true positive}}}$ related to the use or not of the $P_I^{2}$ when all other parameters are kept identical. The results show a better fit of the simulation when the $P_I^{2}$ is activated for the Etna steep slopes. The parameters used in these simulations are the standard ones defined in Table 2 ($L_{\text{max}}$-Etna =8.442 m, $L_{\text{max}}$-Nyamuragira =19.551 m).
unknown eruption rate. The method can be used for short-term forecasting if we suppose that the ongoing lava flow has the same characteristics as the ones that have already settled on the same volcano. Like with $L_{\text{max}}$, the pixels with highest probabilities are located in the main channel and the patterns observed in the real lava flow are well represented (Fig. 10b). Even if the length is overestimated, pixels located further from the real lava flow front have lower probabilities to be inundated.

$L_{\text{flowgo}}$ requires the input of many parameters influencing the lava flow evolution on the topography (Table 3). These parameters are not often available, are difficult to predict and may vary depending on the eruption (Damiani et al., 2006). Therefore, $L_{\text{flowgo}}$ is aimed at expert users with sufficient knowledge on the lava flows to be modelled. Effusion rate may vary during an eruption but taking into account the peak discharge and the standard parameters (Table 3), predictions can be made about the 2001 Etna (Fig. 10c) and 2006 Nyamuragira lava flow extent. In the $L_{\text{flowgo}}$ method the slope is of great importance, since it influences the lava flow velocity and cooling rate, which are both key parameters controlling the length reached by the lava before lava flow stops. The length reached by every flow line is therefore not always the same because the slopes encountered by the lava flow vary for the different flow lines (Table 4). The mean distances reached by the flow lines corresponds to ~80% of the actual flow length, which is consistent with the fact that FLOWGO simulates the length of the channelized section of the lava flow but is not representing the dispersed flow front (Lipman et al., 1985; Rowland et al., 2005).

### 4.3. Influence of the DEM resolution on the simulations

Nowadays, DEMs of different spatial resolution are easily available. However, DEM resolutions majorly influence the simulations. The first implication of DEM resolution is its impact on setting the initial parameters values. Tests demonstrated that the optimum $H_c$ value varies with resolution but tends to the minimum observed flow thickness. The $H_p$ parameter is of high importance especially with high resolution DEMs. A low to zero probability threshold has to be chosen when working with a high resolution DEM, while a higher threshold...
should be defined with low resolution DEMs.

Secondly, simulations on high resolution DEMs contain more geometric detail and path possibilities (Fig. 11) (Tarquini et al., 2012). The increase of detail nevertheless goes along with an increase of computation time (Connor et al., 2012). The probability of a pixel to be inundated (PROB) is most of the time lower than with low resolution DEMs (Fig. 12).

Third, the DEM resolution impacts the lava flow length. Taking the length reached by the historical lava flow as the maximum length ($L_{\text{max}}$) induces an underestimation of the maximum length reached by the simulated lava flows, especially with high DEM resolution. Every pixel through which the lava flow propagates is accounted for in calculating the distance separating the lava flow front from the vent. The travelled distance of the lava flow is thus always larger than the crow flies distance. Based on simulation results of the 2001 Etna flow we estimate that, for steep slopes and for a 90 m DEM resolution, maximum length ($L_{\text{max}}$) has to be increased with a factor of ~1.13, whereas this factor is ~1.26 for 30 m resolution DEMs and ~1.86 for 10 m resolution DEMs. On more gentle slopes, as for the 2006 Nyamuragira flow, estimates are of ~1.14 for 90 m resolution DEMs and ~1.47 for 30 m resolution DEMs.

Finally, FIs obtained with similar parameters but different DEM resolutions cannot be compared to one another. The surface covered by simulations realized on lower resolution DEMs is inevitably more important than with higher resolution DEMs and will reach higher FIs. Using an accurate and up-to-date DEM is of great importance. Changes in the topography over time affect the preferential path taken by lava flow simulations (Tarquini and Favalli, 2010). Fig. 12 demonstrates that modification of the topography yields contrasting results and this has to be taken into account while trying to simulate a historical flow whose topography is already included in the DEM or while simulating future lava flow hazard.

While DEM accuracy is not explicitly addressed in this study, it is important to mention that simulation results will be affected by uncertainty in the DEM. The sensitivity of the outcome of spatial models to DEM error is influenced by terrain characteristics as well as by the spatial structure of the error (Canters et al., 2002; Hengl et al., 2010; Hunter and Goodchild, 1997), and is likely to increase with model resolution (Zhou and Liu, 2004).

Finally, the DEM resolution also influences the modelled lava flow length with FLOWGO. Opposite trends are observed for the mean length reached by lava flows emplaced on gentle (Nyamuragira) and steep (Etna) slopes (Table 4). On gentle slopes, the majority of the lava flow lines reaches the real lava flow front on a lower resolution DEM, while on steep slopes the majority of the lava flow lines reaches the real lava flow front on a higher resolution DEM. This can be attributed to the effect of DEM resolution on the smoothing of slopes (Kerry et al., 2008; Vaze et al., 2010). With low resolution DEMs, the elevation is averaged leading to a smoothing of the slopes distribution. At lower spatial resolutions, there is an increase of the minimum elevation values and a decrease of the maximum elevation values. Low angle slopes with local flat areas, where the flow velocity can drop to zero at high DEM resolution, are then characterized by more homogenous slopes, preserving positive velocities, whereas steep slopes are reduced by the spatial averaging, therefore decreasing the flow velocity and final length (Vaze et al., 2010). Selection of an appropriate DEM resolution is therefore of great importance when using the $L_{\text{flowgo}}$ method, in addition to all the other thermo-rheological variables not discussed here.

5. Prospects

In contrast to volume-limited models, the output of Q-LavHA does not simulate the deposition of specific lava volume or thickness on each inundated cell. It is therefore unable to simulate the temporal evolution of the topography induced by the lava emplacement and its impact on
Table 3
Standard parameters used for Lflowgo simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Etna</th>
<th>Sources</th>
<th>Nyamuragira</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusivity</td>
<td>$E_r$</td>
<td>m$^3$ s$^{-1}$</td>
<td>30.68</td>
<td>(Coltelli et al., 2007)</td>
<td>155</td>
<td>(Coppola and Cigolini, 2013)</td>
</tr>
<tr>
<td><strong>Channel dimension</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel width-depth ratio</td>
<td>$w/r$</td>
<td>–</td>
<td>6.19</td>
<td>(Harris per. com.)</td>
<td>0.75</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td><strong>Velocity constant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity</td>
<td>$g$</td>
<td>m s$^{-2}$</td>
<td>9.81</td>
<td>–</td>
<td>9.81</td>
<td>–</td>
</tr>
<tr>
<td><strong>Viscosity and yield strength parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity at eruption</td>
<td>$\eta$</td>
<td>Pa s</td>
<td>3766.76</td>
<td>(Harris per. com.)</td>
<td>100</td>
<td>(Whittington A per. com.)</td>
</tr>
<tr>
<td>a constant</td>
<td>$a$</td>
<td>K$^{-1}$</td>
<td>0.04</td>
<td>(Dragoni, 1989)</td>
<td>0.04</td>
<td>(Dragoni, 1989)</td>
</tr>
<tr>
<td>b constant</td>
<td>$b$</td>
<td>Pa</td>
<td>0.01</td>
<td>(Dragoni, 1989)</td>
<td>0.01</td>
<td>(Dragoni, 1989)</td>
</tr>
<tr>
<td>c constant</td>
<td>$c$</td>
<td>K$^{-1}$</td>
<td>0.08</td>
<td>(Dragoni, 1989)</td>
<td>0.08</td>
<td>(Dragoni, 1989)</td>
</tr>
<tr>
<td><strong>Radiation parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stephan-Boltzmann constant</td>
<td>$\sigma$</td>
<td>W m$^{-2}$ K$^{-4}$</td>
<td>5.67E-08</td>
<td>–</td>
<td>5.67E-08</td>
<td>–</td>
</tr>
<tr>
<td>Emissivity of basal</td>
<td>$e$</td>
<td>–</td>
<td>0.95</td>
<td>(Cordonnier et al., 2014)</td>
<td>0.95</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td><strong>Conductivity parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lava thermal conductivity</td>
<td>$k_{lava}$</td>
<td>W m$^{-1}$ K$^{-1}$</td>
<td>2</td>
<td>(Cordonnier et al., 2014)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Temperature at base of basal crust</td>
<td>$T_{lava}$</td>
<td>°C</td>
<td>500</td>
<td>(Harris per. com.)</td>
<td>700</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>Thickness of basal crust</td>
<td>$H_b$</td>
<td>%</td>
<td>19</td>
<td>(Harris per. com.)</td>
<td>19</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td><strong>Thermal conductivity</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eruption temperature</td>
<td>$T_{erup}$</td>
<td>°C</td>
<td>1100</td>
<td>(Cordonnier et al., 2014)</td>
<td>1140</td>
<td>(Coppola and Cigolini, 2013)</td>
</tr>
<tr>
<td>Crust temperature</td>
<td>$T_{crust}$</td>
<td>°C</td>
<td>150</td>
<td>(Harris per. com.)</td>
<td>550</td>
<td>(Coppola and Cigolini, 2013)</td>
</tr>
<tr>
<td>Difference of temperature between $T_{erup}$ and $T_{crust}$</td>
<td>$T_{erup} - T_{crust}$</td>
<td>°C</td>
<td>500</td>
<td>(Harris per. com.)</td>
<td>160</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>d constant</td>
<td>d</td>
<td>–</td>
<td>–0.00756</td>
<td>(Harris per. com.)</td>
<td>–0.16</td>
<td>–</td>
</tr>
<tr>
<td><strong>Density and vesicularity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dense-rock equivalent density</td>
<td>$\rho_{eq}$</td>
<td>kg m$^{-3}$</td>
<td>2700</td>
<td>(Cordonnier et al., 2014)</td>
<td>2775</td>
<td></td>
</tr>
<tr>
<td>Vesicularity</td>
<td>$\Phi_v$</td>
<td>%</td>
<td>22</td>
<td>(Harris and Rowland, 2015)</td>
<td>25</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td><strong>Convection parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>U</td>
<td>m s$^{-1}$</td>
<td>5</td>
<td>(Harris and Rowland, 2001)</td>
<td>5</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>Friction wind speed / wind speed$^2$</td>
<td>$C_w$</td>
<td>–</td>
<td>0.0036</td>
<td>(Harris and Rowland, 2001)</td>
<td>0.0036</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>Air temperature</td>
<td>$T_{air}$</td>
<td>°C</td>
<td>25</td>
<td>(Cordonnier et al., 2014)</td>
<td>20</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>Air density</td>
<td>$\rho_{air}$</td>
<td>kg m$^{-3}$</td>
<td>0.4412</td>
<td>(Harris and Rowland, 2001)</td>
<td>0.4412</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>Air specific heat capacity</td>
<td>$c_{air}$</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
<td>1200</td>
<td>(Cordonnier et al., 2014)</td>
<td>1099</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td><strong>Crystal parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass fraction of crystals upon eruption</td>
<td>$\Phi_{plu}$</td>
<td>–</td>
<td>0.3</td>
<td>(Harris per. com.)</td>
<td>0.1</td>
<td>(Pouclet, 1976)</td>
</tr>
<tr>
<td>Rate of crystallization</td>
<td>$dL/dT$</td>
<td>–</td>
<td>0.005</td>
<td>(Harris per. com.)</td>
<td>0.0027</td>
<td>(Pouclet, 1976)</td>
</tr>
<tr>
<td>Latent heat of crystallization</td>
<td>$L$</td>
<td>J kg$^{-1}$</td>
<td>209,000</td>
<td>(Cordonnier et al., 2014)</td>
<td>356,000</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
<tr>
<td>Inverse of maximum crystal concentration</td>
<td>R</td>
<td>–</td>
<td>1.51</td>
<td>(Harris and Rowland, 2015)</td>
<td>1.51</td>
<td>(Harris and Rowland, 2001)</td>
</tr>
</tbody>
</table>

Even though probabilistic approaches for lava flow simulation are based on simple assumptions, corrective factors are easy to apply in Q-LavHA and enable us to realistically simulate the emplacement of lava. Calibration of the $H_t$ and $H_p$ parameters can be based on, respectively, the observed minimum and maximum lava thickness. Squared weighting of elevation differences in the calculation of lava flow inundation probabilities and a minimum of 1500 iterations is recommended. The probability threshold has to be adapted based on the DEM resolution used and the purpose of the simulations. The best DEM resolution to use with Q-LavHA depends on the amount of detail desired, the available computational time and the purpose of the simulation. It is recommended to maintain a proper balance between all these elements. Finally, the users have to select the most appropriate lava flow length constraint, based on available data and knowledge about the lava flows to be modelled.

The probabilistic lava flow map produced by Q-LavHA should be interpreted with care. Q-LavHA attempts to approach the reality of a channelized ‘a‘a lava flow inundation as accurately as possible. However, the outcome of the simulation depends on the quality of the DEM used and the selected simulation parameters. The probability of being inundated has to be interpreted as having a higher or a lower chance to be inundated. We consequently recommend the users to interpret the results as the sum of the trajectories a flow can potentially follow if an eruption occurs.

**6. Conclusion**

Q-LavHA is a free plugin running in an open-source software environment. It allows users to simulate channelized ‘a‘a lava flows from a point, line or surface vent source on DEMs, using a combination of probabilistic and thermo-rheological model components. Its user-friendly interface and its flexibility enables the use of the plugin by both novice and experienced users, in different environments where knowledge on lava flow properties might be available or not.

subsequent lava flow branches. In the future, Q-LavHA will be integrated in the VOLCANBOX, a new software platform that integrates tools for long- and short-term hazard assessment and for the management of volcanic risk, with as final aim to support stakeholder’s decisions (Martí et al., 2016).

Table 4
Evolution of the mean distance reached by the simulated flows when the Lflowgo is activated, regarding different DEM resolutions. The parameters used for these simulations are the standard ones define in Table 3.

<table>
<thead>
<tr>
<th>DEM resolution</th>
<th>90 m</th>
<th>30 m</th>
<th>10 m</th>
<th>Real length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentle slopes (Nyamuragira 2006 lava flow)</td>
<td>11.200 m</td>
<td>10.480 m</td>
<td>/</td>
<td>13.300 m</td>
</tr>
<tr>
<td>Steep slopes (Etna 2001 lava flow)</td>
<td>4.277 m</td>
<td>5.255 m</td>
<td>6.630 m</td>
<td>6.700 m</td>
</tr>
</tbody>
</table>
Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2016.09.003.

References


