LLUNPIY Preliminary Extension for Simulating Primary Lahars
Application to the 1877 Cataclysmic Event of Cotopaxi Volcano

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Keywords: Modelling, Simulation, Cellular Automata, Lahars, Cotopaxi, Natural Hazard, LLUNPIY.

Abstract: Cotopaxi volcano is one of the most studied and surveyed volcanos in the world because the repetition of the 1877 catastrophic lahar invasion, is not implausible, threatening now more than 100,000 persons. A reliable forecasting tool is very important for projecting security measures. LLUNPIY is a Cellular Automata model for simulating lahars in terms of complex system evolving on the base of local interaction. Here, LLUNPIY extension is applied to Cotopaxi event of 1877 primary lahars, after the successful simulation of some secondary lahars of Tungurahua volcano. Such an extension permitted simulations with different initial hypotheses: our preliminary simulations agree in outline with field studies about the evolution of event, moreover LLUNPIY permits a broader approach to overall phenomenon in comparison with other tools.

1 INTRODUCTION

Volcanic eruptions can generate directly (primary lahars) or indirectly (secondary lahars) catastrophic surface flows that are a mixture of volcanic debris and water occurring on and around volcanoes (Vallance, 2000), other than normal streamflow (Smith and Fritz, 1989), with consistency, viscosity and approximate density of concrete: they are fluid, when sloping moving up to 100 km/h as far as extreme distance of 300 Km, solid at rest in the flat terminal zone (Hoblitt et al., 1987). They may be primary lahars, for instance, when lava or pyroclastic flows melt snow and glacier and/or mix with wet soil generating a flood sometime also with the water of broken basin (Manville et al., 2013; Pistolesi et al., 2014). Typical instances are the 1949, 1963 e 1971 lahars at Villarica, Chile (Vallance, 2005), when lava flows melted snow and glacier and broke a pond. Secondary lahars instead occur from the post-eruptive when heavy rainfalls, typhoons or lake breakout mobilize ash and other volcanic debris of previous volcanic activities (e.g. 2005, 2008 lahars of Tungurahua volcano simulated by Partial Differential Equations (PDE) and Cellular Automata (CA) methods (Williams et al., 2008; Machado., et al. 2014).

Lahars are very complex dynamical systems, very difficult to be modelled: they can grow by soil erosion and/or incorporation of water, along watercourses. Unconsolidated pyroclastic material, (Major et al., 2000; Manville et al., 2000), can be easily eroded by superficial water forming dilute sediment-laden flows, that can bulk-up to debris flows whose magnitude will depend upon the volume of both the water and remobilized material (Barclay et al., 2007).

A variety of approaches have been taken to model the behaviour of lahars and the hazards posed to downstream communities (Manville et al., 2013): empirical models based on smart correlations of phenomenon observables (Schilling, 1998; Muñoz-Salinas et al., 2009), simple rheological and hydrological models, which assume acceptable simplifications as composition-independent flow behaviour or Newtonian flow behaviour (Costa, 2004; O'Brien et al., 1993), PDE approximating numerical methods of complex physical behaviour of lahar (Pitman et al., 2003).

CA represent an alternative methodological approach for modelling and simulating complex systems evolving on the base of local interactions. Intuitively, a CA can be seen as a space, partitioned in regular cells, each one embedding an identical

Machado G., Lupiano V., Crisci G. and Di Gregorio S..
LLUNPIY Preliminary Extension for Simulating Primary Lahars - Application to the 1877 Cataclysmic Event of Cotopaxi Volcano.
DOI: 10.5220/0005542903670376
In *Proceedings of the 5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2015), pages 367-376
ISBN: 978-989-758-120-5

input/output computing unit. Each cell is characterized by its state. S is the finite set of the states. Input for each cell is local and is given by the states of m neighbouring cells, where the neighbourhood conditions are given by a pattern invariant in time and space. At time 0, cells are in arbitrary states (initial conditions) and the CA evolves changing simultaneously the state at discrete times, according to (local, depending on the input) rules, that are invariant in time and space.

Surface flows are a typical application of Multicomponent (or Macroscopic) Cellular Automata (Di Gregorio and Serra, 1999; Avolio et al., 2003) for computer simulation: SCIARA model for lava flows (Avolio et al., 2006), SCIDDICA (Avolio et al., 2010) for debris flows, PYR (Crisci et al., 2005) for pyroclastic flows, VALANCA (Avolio et al., 2010) for snow avalanches, SCAVATU (D'Ambrosio et al., 2001) for soil erosion by rainfall.

A very important characteristic of all these models is that they are based on two dimensions CA, but they work effectively in three dimensions because the third dimension is enclosed in part of the sub-states: altitude, kinetic head, lahar thickness, depth of erodible pyroclastic stratum, and so on.

We developed LLUNPIY in a first version for simulating secondary lahars with applications to 2005 and 2008 Tungurahua lahars. An extension was performed in order to capture the behaviour of primary lahars and two different applications related to initial phase were accomplished for 1877 Cotopaxi catastrophic lahars.

The second section of the paper describes the geological features of the phenomenon related to Cotopaxi volcano characteristics. The third section is devoted to the LLUNPIY model applied to the simulations that are presented in the fourth section. At the end comments and conclusions.

2 COTOPAXI VOLCANO

Cotopaxi volcano is situated in the Eastern Cordillera of the Ecuadorian Andes (Figure 1) about 60 km south of Quito, and it is a very hazardous active stratovolcano.

With an altitude of 5897 m a.s.l. the summit of the volcano is currently covered with a thick layer of ice that ranges between 30 and 120 m (Cáceres et al., 2004). Cáceres et al. (2004) estimated that the glacier volume was approximately 1,000 million m^3 in 1976, considering an average thickness of 50 m. Such a volume has been reduced to 732 million m^3 in 1997, because of a progressive melting, probably generated by climate change.

The main drainage lines are: in north sector there is the Pita-Guayallabamba River, the west slopes are crossed by several tributaries of the Napo River, while waters of several streams, often encased in narrow valleys, coming from the cone of volcano, converge into the Rìo Cutuchi, that flows toward south-southwest in the wide valley of Latacunga.

Figure 1: Cotopaxi volcano and its surrounding region.

The area around the volcano is densely populated, in fact, the city of Quito is located in north. In the Cutuchi valley besides several villages, there are the towns of Latacunga and Salcedo, respectively 45 km and 50 km in south of Cotopaxi. In addition, industries and agriculture are intensively developed in these areas.

Since 1738 Cotopaxi has erupted more than 50 times. The most violent historical eruptions were in 1744, 1768, 1877, and 1904 with generation of disastrous lahars in many cases.

2.1 1877 Lahars

The presence of glacier on summit of Cotopaxi is one of principal causes, together with volcanic eruptions (lava or pyroclastic flows), of primary lahars. In fact, the Cotopaxi has often produced catastrophic lahars during eruptions because of ice and snow melting.

The 1877 eruption, described by Sodiro (1877) and Wolf (1878), produced very destructive and large lahars. These chronicles report times and extension of lahar floods next to inhabitant centres: some later observations estimated the glacier melting to 1/10 of total volume (Wolf, 1878). Water, which originates from melting glacier, had been mixed with pyroclastic material erupted and with pre-existing volcanoclastic materials outcropping along slopes, so many lahars flows had been generated (Figure 2). These flows, channelled in drainage network, destroyed population centres and everything on the path.

On the western slope of volcano, three main flows are generated, coming down with a conjectured speed from about 30 m/s to about 10 m/s (depending on the slope) and reaching Latacunga, a village, at that time, in about one hour (Mothes et al., 2014).

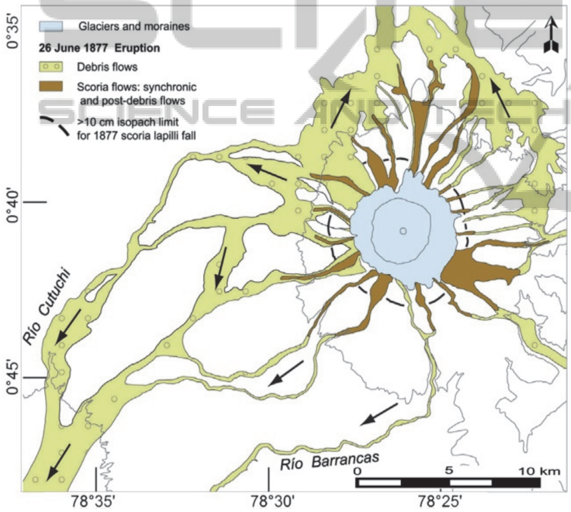

Figure 2: Reconstruction of 1877 lahar path (from Mothes et al., 2014).

3 LLUNPY MODEL

In this section, we present an extension of LLUNPIY model with the purpose of capturing the dynamical behaviour of primary lahars in the southern drainage system of the Cotopaxi volcano.
LLUNPIY (**L**ahar modelling by **L**ocal rules based on an **UN**derlying **PI**ck of **Y**oked processes) derives from the Quechua word llunp'iy, that means flood.

The first version has been developed to simulate secondary lahars with applications to two events at Tungurahua volcano (Machado et al., 2014 and 2015).

Lahars triggered by mobilization of deposits from volcanic explosions have occurred at Cotopaxi volcano, Ecuador on the average of once every century over the last two millennia. Lahars from Cotopaxi are possible to flow down along three main drainages, affecting a present day population of around 100,000 inhabitants.

Primary lahars were modelled using LLUNPIY in three main stages. Generation stage: lahars are generated from pyroclastic flows and melting of the volcano's icecap, due to interaction of eruptive products with a summit glacier. This stage, the glacier melting, is an extension of the previous version of LLUNPIY, that models raining, water flows and percolation in the soil and successive mobilization of pyroclastic stratum; the raining contribute is zero for the Cotopaxi event. Flood stage: lahar flows develop along the volcano steep slopes with high gravitational potential energy and turbulence with possible soil erosion and water inclusion along watercourses. Final stage: the lahar flow reduces its kinetic energy and velocity in flat areas; rapid decrease of turbulence causes deposit and solidification processes by water extrusion; in some cases, lahar can partially "be diluted" and "disappear", if it runs into a watercourse with a water flow, enough large to englobe the lahar matter.

3.1 Formal Definition of LLUNPIY

The extension of LLUNPIY model is a two dimensional CA with hexagonal tessellation and defined by the septuplet:

$$\langle \boldsymbol{R}, \boldsymbol{G}, \boldsymbol{X}, \boldsymbol{S}, \boldsymbol{P}, \tau, \gamma \rangle \qquad (1)$$

- $\boldsymbol{R} = \{(x, y) | x, y \in \mathbb{N}, 0 \leq x \leq l_x, 0 \leq y \leq l_y\}$ is the set of points with integer co-ordinates, that individuate the regular hexagonal cells, covering the finite region, where the phenomenon evolves. $\mathbb{N}$ is the set of natural numbers;
- $\boldsymbol{G} \subseteq R$ is the set of cells, corresponding to the glacier, where lahar is formed when pyroclastic matter melts ice;
- $\boldsymbol{X} = \{(0, 0), (1, 0), (0, 1), (-1, 1), (-1, 0), (0,-1), (-1,-1)\}$, the neighbourhood index, identifies the geometrical pattern of cells, which influence state change of the "central" cell (Figure 3): the central cell (index 0) itself and the six adjacent cells (indexes 1,..,6);
- $\boldsymbol{S}$ is the finite set of states of the finite automaton, embedded in the cell; it is equal to the Cartesian product of the sets of the considered sub-states (Table 1).
- $\boldsymbol{P}$ is the set of the global physical and

empirical parameters, which account for the general frame of the model and the physical characteristics of the phenomenon (Table 2);

- $\tau : S^7 \rightarrow S$ is the cell deterministic state transition in R, it accounts for the following main components of the phenomenon: lahar flow, soil mobilization and erosion. Water inclusion and extrusion, lahar solidification are not considered for Cotopaxi case, because such primary lahars followed the river paths and largely overflowed, they lost in the ocean during the final phase;
- $\gamma{:}\mathbb{N}{\times}G \rightarrow S$ expresses the "external influence" of fall of the pyroclastic matter on glacier and consequently ice state change in lahar with the addition of pyroclastic matter for G cells at the initial CA steps. ℕ is here referred to the step number.

Table 1: Sub-states regarding the generation phases.

SUB-STATES	DESCRIPTION
S_A, S_{IT}	cell **A**ltitude, **I**ce **T**hickness,
S_{LT}, S_{KH}, S_{LWC}	**L**ahar **T**hickness, **L**ahar **K**inetic **H**ead, **L**ahar **W**ater **C**ontent
S_X, S_Y	the co-ordinates **X** and **Y** of the lahar barycenter inside the cell
S_E, S_{EX}, S_{EY}, S_{KHE} (6 components)	**E**xternal flow normalized to a thickness, **E**xternal flow co-ordinates **X** and **Y**, **K**inetic **H**ead of **E**xternal flow
S_I, S_{IX}. S_{IY}, S_{KHI} (6 components)	**I**nternal flow normalized to a thickness, **I**nternal flow co-ordinates **X** and **Y**, **K**inetic **H**ead of **I**nternal flow

3.2 Generalities of τ and γ

In the formulae, a sub-state is specified by S, its right subscript is a shortening of the sub-state name in capital letters (e.g., S_A, the sub-state altitude); if the left subscript is not specified, the sub-state is related to the central cell of the neighbouring; when other cells of the neighbouring must be considered, the left subscript specifies the index of the neighbouring cell, e.g., ${}_1S_A$, is the sub-state altitude of the cell with index 1 in the neighbouring. Sum of indexes of opposite cells is always 7 as in Figure 3.

S_X' indicates the updated value of the generic sub-state S_X. ΔS_x means S_X value variation.

Quantities related to volumes as outflows are normalized to lengths, because the cell area is constant in value.

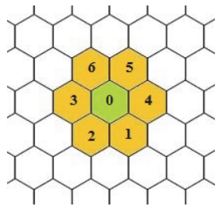

Figure 3: Geometrical pattern of cells.

Table 2: Physical and empirical parameters.

PARAMETERS	DESCRIPTION
p_a, p_t	cell **a**pothem (m), **t**emporal correspondence of a CA step (s)
p_{fc}	**f**riction **c**oefficient parameter (°)
p_{td}, p_{ed}, p_{pe}, p_{mt}	lahar parameters: **t**urbulence **d**issipation (-) and **e**rosion **d**issipation (-) of energy; lahar parameter of **p**rogressive **e**rosion (-), **m**obilization **t**hreshold (m)
p_{slt}	**sl**ope **t**hreshold (°)
p_{khl}	**k**inetic **h**ead **l**oss (m)

The lahar inside a cell is modelled as a "cylinder" tangent the next edge of the hexagonal cell with mass, velocity and barycentre co-ordinates. Movements of cylinders from central cell toward adjacent cells originate: internal flows (cylinder shift is all inside the cell), external flows (cylinder shift is all outside the cell) and mixed situations.

Computations of lahar flows are based on the Algorithm of the Minimization of Differences (AMD) for determination of minimizing outflows f_i $1 \leq i \leq 6$, (i.e., the flows that minimize differences in height for the cell neighbourhood) and the determination of outflow shifts (Di Gregorio and Serra, 1999; Avolio et al., 2012). AMD involves different specification of "heights" h_i, the "fixed" parts and d, the "distributable" part. Motion equations specify a shift x and a final velocity v, in order to determine from initial f_i ($1 \leq i \leq 6$) the outflows f_i' ($0 \leq i \leq 6$) during a step. Lahar kinetic head is obtained by:

$$S_{KH} = \frac{v_l^2}{2g} \qquad (2)$$

where g is the gravity acceleration, the subscripts l means lahar.

The application of γ function is here simplified: $S'_{LT} = S_{IT}$ and $S'_{IT} = 0$ in the first step.

3.3 Specification of τ

The main "elementary processes" of LLUNPIY are outlined in the following.

3.3.1 Lahar Thickness and Outflows

Lahar in the cell and its lahar outflows are computed in similar way as debris in the cell and its debris flow in SCIDDICA-SS2 and improvements (Avolio et al., 2008; 2009; Lupiano et al., 2014a; 2014b). SCIDDICA means **S**imulation through **C**omputational **I**nnovative methods for the **D**etection of **D**ebris flow path using **I**nteractive **C**ellular **A**utomata, while SS2 means second version for both **S**ubaerial and/or **S**ubaqueous debris flow simulation.

The outflow path from the central cell to a neighbouring cell *i* follows an ideal direction between two points: the lahar barycentre of central cell and the centre of the adjacent cell *i* accounting for slope θ_i (Figure 3).

Viscosity is modelled as the part of lahar thickness, that cannot be movable (Avolio et al., 2006) according to a function that computes an "adherence" value between two values p_{adh1} and p_{adh2} in linear way.

Viscosity represents "de facto" the lahar deposit along the path at the phenomenon ending except the solidification deposit.

In the case of this primary lahar, adherence is a constant value p_{adh} in order to account the catastrophic features of the phenomenon with an enormous quantity of melted water, plus the river water, so that the lahar keeps extremely fluid.

AMD is so applied:

$$d = {}_0S_{LT} - p_{adh} \quad (3)$$

$$h_0 = {}_0S_A + {}_0S_{KH} + P_{adh} \quad (4)$$

$$h_i = {}_iS_A + {}_iS_{LT} \quad (5)$$

The motion equations are related to outflows from central cell toward the adjacent cell *i* ($1 \le i \le 6$):

$$x_i = v_0 p_t + g(\sin\theta_i - p_{fc} \cdot \cos\theta_i)\frac{p_t^2}{2} \quad (6)$$

$$v_i = v_0 + g(\sin\theta_i - p_{fc} \cdot \cos\theta_i)p_t \quad (7)$$

where v_0 is the initial velocity (deduced by S_{KH}), x_i is the shift of the outflow toward the cell *i*, θ_i is the slope angle between the central cell and the neighbour *i*;

Sub-states regarding outflows are computed in the same way as debris flows in SCIDDICA-SS2 (Avolio et al. 2008).

S'_{LT}, S'_{KH}, S'_X, S'_Y are computed by balancing equations that consider the contribute of outflows and inflows:

$$ {}_0S'_{LT} = {}_0S_{LT} + \sum_{i=1}^{6}\left({}_iS_{E(7-i)} - {}_0S_{Ei}\right) \quad (8)$$

where ${}_iS_{E(7-i)}$ is the outflow of neighbouring cell *i* toward the cell 0, that is specified by component 7-*i* for the neighbouring of cell *i*. An average weight is also considered:

$$ {}_0S'_{KH} = \frac{{}_0S_{KH}\ {}_0S_{LT}}{{}_0S'_{LT}} + \frac{\sum_{i=1}^{6}\left({}_iS_{E(7-i)}\ {}_iS_{KH} - {}_0S_{Ei}\ {}_0S_{KH}\right)}{{}_0S'_{LT}} \quad (9)$$

$$ {}_0S'_X = \frac{{}_0S_X\left({}_0S_{LT} - \sum_{i=1}^{6}\left({}_0S_{Ii} + {}_0S_{Ei}\right)\right)}{{}_0S'_{LT}} + \frac{\sum_{i=1}^{6}\left({}_0S_{Ii}\ {}_0S_{IXi} + {}_iS_{E(7-i)}\ {}_iS_{EX(7-i)}\right)}{{}_0S'_{LT}} \quad (10)$$

$$ {}_0S'_y = \frac{{}_0S_y\left({}_0S_{LT} - \sum_{i=1}^{6}\left({}_0S_{Ii} + {}_0S_{Ei}\right)\right)}{{}_0S'_{LT}} + \frac{\sum_{i=1}^{6}\left({}_0S_{Ii}\ {}_0S_{IYi} + {}_iS_{E(7-i)}\ {}_iS_{EY(7-i)}\right)}{{}_0S'_{LT}} \quad (11)$$

A turbulence effect is modelled by a proportional kinetic head loss at each LLUNPIY step: $-\Delta S_{KH} = p_{khl}S_{KH}$. The turbulence affects kinetic head and consequently the velocity. This formula involves that a velocity limit is asymptotically imposed "de facto" for any value of slope.

3.3.2 Soil Erosion

When the kinetic head value overcomes an opportune threshold ($S_{KH} > p_{mt}$) depending on the soil features then a mobilization of the pyroclastic cover occurs proportionally to the quantity overcoming the threshold:

$$p_{pe}(S_{KH} - p_{mt}) = \Delta S_{LT} \quad (12)$$

because the pyroclastic cover depth diminishes as the debris thickness increases); the kinetic head loss is:

$$-\Delta S_{KH} = p_{ed}(S_{KH} - p_{mt}) \quad (13)$$

The mixing of the eroded pyroclastic cover with the earlier debris involves that the earlier debris kinetic energy becomes the kinetic energy of all the mass of debris, it implicates trivially a further kinetic head reduction:

$$S'_{KH} = \frac{(S_{KH} - \Delta S_{KH})}{S_{LT} + \Delta S_{LT}} \quad (14)$$

4 SIMULATIONS OF 1877 EVENT

Necessary input data for simulation of primary lahars with LLUNPIY are:

- DEM (Digital Elevation Model) with adequate cell-size;
- Source areas: extension of glaciers, whose melting originates lahars, or extension of ponds/lakes, whose destruction by volcanic matter releases enough water to generate lahars;
- Specifications of volcanic activity (eruption duration, strength and range of action) that effects glacier melting and/or destruction of ponds/lakes;
- Detachment areas: this is an alternative to simulate volcanic activity, the phenomenon starts in the areas immediately out of the volcanic action range by specifications of “initial” quantities of lahar;
- Erodible pyroclastic cover.

In order to calibrate model parameters it is fundamental to identify the lahar path and invaded area of real phenomenon in order to measure the simulation “goodness”.

We referred for 1877 event simulation to the 2010 DEM with 30m cell size with vertical accuracy from 0.6 m to 1.3 m (supplied to us by Instituto Geofísico of the Escuela Politécnica Nacional - IGEPN), that is a very large size but considering the magnitude and extent of the phenomenon was considered acceptable, if changes in the time are also considered. Erodible detrital cover was considered a uniform layer of 5 m thick because field data are not available in all the simulation area.

4.1 “Many Sources” Simulations

We considered, as first approach, the hypothesis (Mothes et al., 2014; Pistolesi et al., 2014) that the main event could be equivalently generated considering the initial positions of lahars sources in the three principal streams (Figure 4b): Río Cutuchi, Río Sasqìmala and Río Barrancas-Alaques.

Only the lahars flowing in the Cutuchi valley were considered, taking into account that the flows toward south may be considered independent from the other ones in the real phenomenon.

In each of these three streams we have placed, respectively, $18.5 \times [10]^6$ m^3, $9.5 \times [10]^6$ m^3 and $10 \times [10]^6$ m^3 of lahar matter.

The resultant simulations are shown in figure 4a. The flows along Río Cutuchi and Río Sasqímala converge together at elevation of 3000 m a.s.l. after 60 minutes of triggering, while the lahar, that flows in Río Barrancas-Alaques, joins the main stream further south in 68 minutes. The simulated lahar flows reached Latacunga in one hour and 30 minutes at average velocity of 8 m/s.

These results are comparable with simulations performed by the model LAHARZ (Pistolesi et al., 2014), that considered larger quantities of initial lahars ($120 \times [10]^6$ m^3 sum of: $60 \times [10]^6$ m^3 in Río Cutuchi, $30 \times [10]^6$ m^3 in Río Sasqímala and $30 \times [10]^6$ m^3 in Río Barrancas-Alaques). Positioning lahar sources in the top of Río Cutuchi,

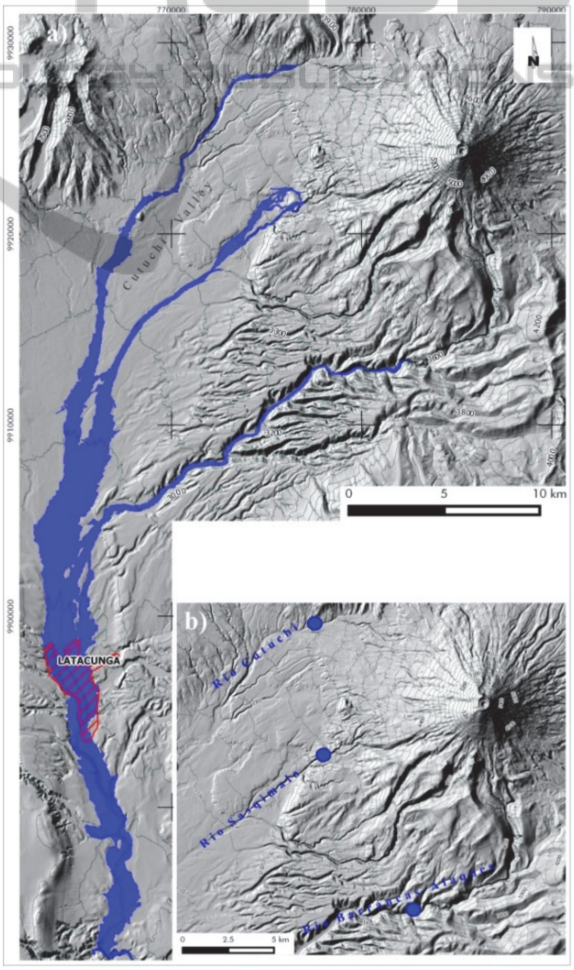

Figure 4: a) LUNPIY simulation of 1877 lahars; b) position of considered lahars sources (blue point).

Río Sasquímala and Río Barrancas-Alaques involves a limit for LLUNPIY because quantity that exceeds greatly the bed of rivers can follow other paths; this may be not justified. Furthermore, LAHARZ does not model soil erosion, which increases lahar flows. LLUNPIY models the erosion that increases the lahar initial quantity. If we compare the reconstruction of the real event, made by Mothes et al. (2014) by field data, the width of LLUNPIY simulation is smaller in the area around the vent, but LAHARZ simulation is larger (Figure 5). In the following phases, the two simulations become always closer. The two results are very similar in the final sector (Latacunga area), because, at the end, the addition of eroded material balances the two approaches. We remember that LAHARZ simulations consider only the lahar extension, but not times and velocity. A further comparison could be possible, considering the glacier melting for LLUNPIY in order to simulate lahars since their very first origin. The next section reports such a case with the worst hypothesis of total icecap melting.

4.2 "Glacier Melting" Simulation

The previous approach with CA involves the limit of initial quantity of lahar at the sources, because overflows can distort the effective evolution of the phenomenon. This did not permit to overcome an initial lahar quantity at the beginning in the previous simulation. For this purpose, we introduce the CA "elementary process" of melting glacier by pyroclastic flows or bombs. The ice layer is supposed to enclose pyroclastic matter and to melt immediately (the LLUNPIY first step) the glacier; that is more realistic than sources approach, if the rapid evolution of eruption is considered. The simulations of icecap melting are based on data, which correspond to 1976 glacier extension with average glacier thickness of 50 m (Cáceres et al., 2004). Simulation initial conditions account only for that part of glacier that is able to feed lahars towards Cutuchi valley (sectors 11-19 in figure 6g).

The evolution of other flows represents partial results only in the first steps of simulation.

In the simulation (Figure 6 a, b, c, d, e, f), lahars reach a maximum height of 50 m in Río Cutuchi and Río Barrancas-Alaques; since the icecap initial melting, the flows join in Cutuchi valley from main drainage lines after 50-60 minutes and reach the town of Latacunga after 1 hour and 35 minutes; that is 35 minutes late in comparison with times, that are reported in the chronicles. These results are comparable with simulations performed by the model LAHARZ, that considered initial larger quantities of lahars in the case of "many sources" simulation, while the worst case of "icecap melting" generated a larger quantity of lahar toward the Cutuchi Valley. The paths are the same, but widths are obviously larger.

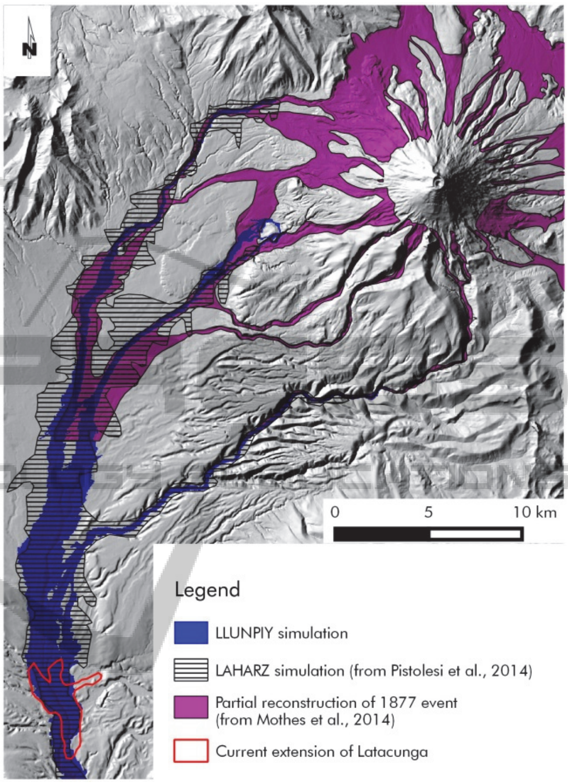

Figure 5: Comparison among LLUNPIY simulation, LAHARZ simulation and partial reconstruction of real event.

5 CONCLUSIONS

We applied LLUNPIY, a CA model, in order to attempt simulations of 1877 primary lahars occurred in Cutuchi Valley, south west sector of Cotopaxi volcano. A careful analysis was performed in order to obtain the most faithful reconstruction of such a catastrophic event.

Simulations were performed by desktop pc with Processor Intel(R) core i7, CPU 2.8GHz and NVIDIA Quadro FX 580 video card. The CA is 1154x1733 cells large.

The adopted programming language is C++, the model is implemented in a "skeleton" fashion, developed for MCA, where the transition function is divided into the "elementary processes" of LLUNPIY. Such elementary processes are executed

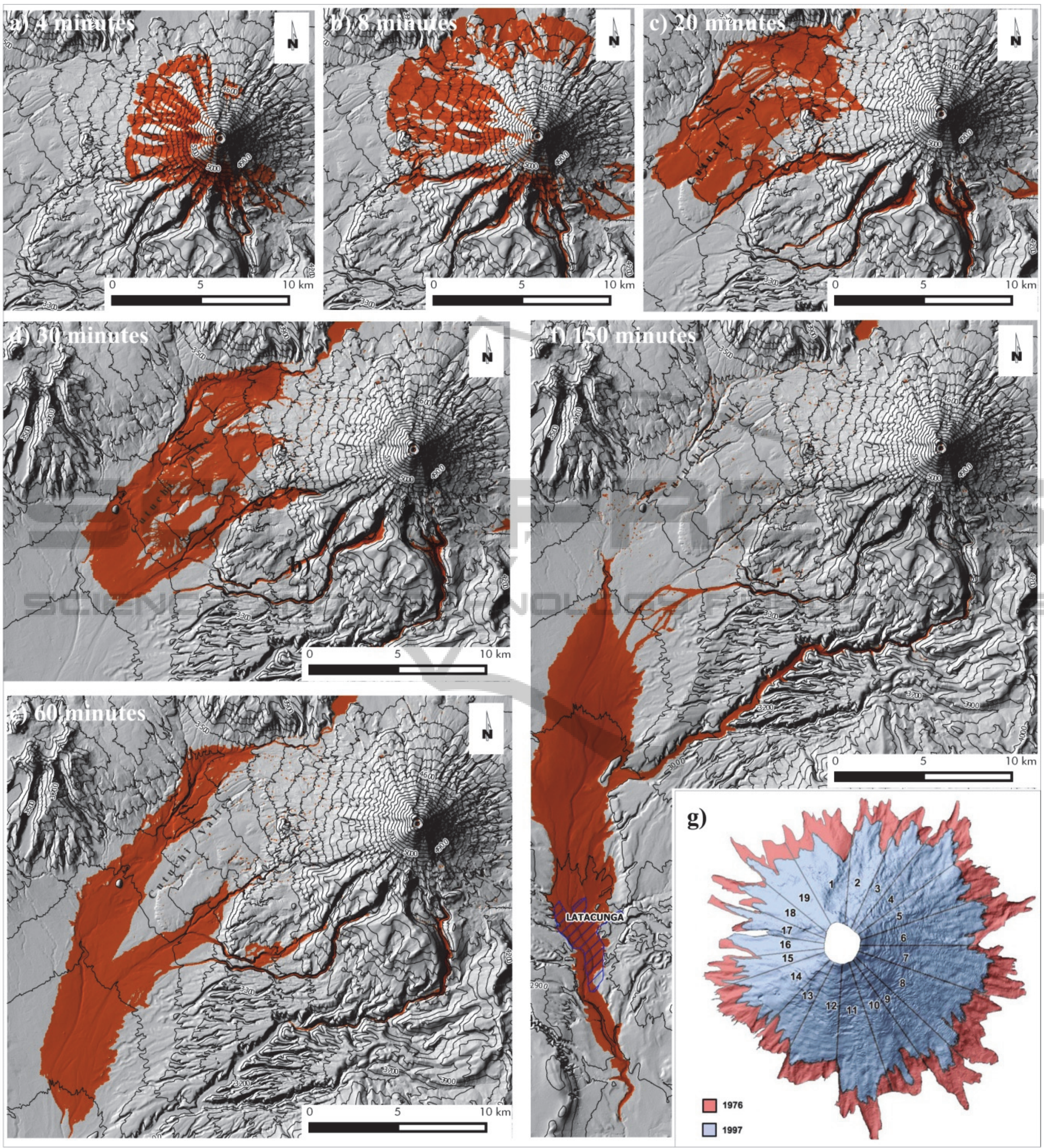

Figure 6: a), b), c), d), e), f) Time steps of glacier melting simulation by trigger moment; g) 1976 glacier extension considered in simulation (from Cáceres et al. 2004).

sequentially in the same order as in section 3. Parallelism was not explicitly activated and the simulation average time is now 5 days, because the implementation of LLUNPIY is not optimized; an optimisation is in progress, it will speed simulations up to 2 days. A parallel version for GPGPU will be developed when the model will be completed for both primary and secondary lahars, in the same way as Spataro et al. (2008).

Some points, which can be improved in the future research work, have to be considered:

We operated on the current morphology; some corrections have to be produced in order to approach the pre-event morphology and to tune better the parameters of LLUNPIY.

Initial velocity of the lahars in the case of “many sources simulations” is null; such simulations can be repeated, starting with an opportune velocity by varying the model and introducing a “lahar source”;

The immediate melting of the Cotopaxi icecap descends from the worst hypothesis among the possible ones, regarding the first phase of the phenomenon; it is important to test the other hypotheses.

Anyway, the results of these preliminary simulations demonstrate that the CA model LLUNPIY is working appropriately, if we consider the partial, sometime rough data concerning the event (Mothes et al., 2014) and its possible improvements.

The simulations were acceptable in terms of reproducing the global dynamics of the events, such as velocity and height of detrital flow. Simulated lahar path and invaded area agree with real (partially reconstructed) one.

Times are not respected: in simulations, lahars reached Latacunga about 30 minutes later than reported in the chronicles of the time (Wolf, 1878). This discrepancy could depend on some imprecision of chronicles or on the increased length of paths in the simulation because of space discretisation or both; we will investigate such a problem by considering these different viewpoints.

Our main future goal concerns the simulation of the overall phenomenon, considering the total icecap melting or partial melting by the effect of pyroclastic bombs. If data will be available, we plan simulating lahars toward the Quito region and the production of hazard scenarios for possible new eruptions of Cotopaxi volcano.

ACKNOWLEDGEMENTS

The authors are grateful to Patricia Mothes, Researcher at IGEPN for obtaining data concerning the Cotopaxi volcano and 1877 eruption, useful information, advices and comments.

The authors thank William Spataro and Maria Vittoria Avolio for critical revision of the manuscript, suggestions and useful advices.

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