Replies to REVIEWER #2

We thank this anonymous reviewer for the useful comments, that help us to clarify some delicate parts of the paper.

1) The description of the model is rather brief!

The description of the model was extended and the model was specified as LLUNPIY/3r in order to distinguish this reduced version from the complete version LLUNPIY for primary and secondary lahars, furthermore the section 1.2 "Multicomponent or Macroscopic Cellular Automata" was added in the "Introduction" in order to introduce the concepts, necessary to better understand the extended description of the model, furthermore all the exemplifications related to "substates" and "elementary processes" of MCA are directly connected to LUNPIY/3r, anticipating and therefore clarifying part of its description.

In particular section 1.2 reads as follows:

"*1.2 Multicomponent or Macroscopic Cellular Automata*

CA are both a parallel computational paradigm and an archetype for modelling "complex dynamical systems", that are extended in the space and can be described evolving mainly on the base of local interactions of their constituent parts. A homogeneous CA can be seen as a d-dimensional space, partitioned in cells of uniform size, each one embedding an identical input/output computing device (a Finite State Automaton). Input for each cell is given by the states of the neighboring cells, where the neighborhood conditions are determined by a pattern invariant in time and space. At the time t=0, cells are in arbitrary states (initial conditions) and the CA evolves changing the state at discrete times simultaneously (CA step), according to the transition function $\sigma: S_m \rightarrow S$*, where S is the finite set of the states and m is the number of the neighbouring cells (Di Gregorio & Serra, 1999).*

A short exemplification is given by the CA Majority: a two dimensions space is divided in square cells, the cell neighborhood is given by the cell itself and the eight surrounding cells, the states are blue (0) and red (1), the transition function calculates the sum of states in the neighborhood, if the sum is more than 4 (the majority of neighbors is red), the next state of the cell will be red otherwise it will be blue. The system evolves from an initial distribution of reds and blues sometime in a complex way, originating local points of expansion of colors (Toffoli, 1984).

When complex macroscopic dynamical systems as phenomena of "surface flows" (lahars, debris flows, snow avalanche, lava flows, and pyroclastic flows) are modelled by CA, the previous definitions are insufficient, Multicomponent or Macroscopic CA (MCA) adopt the following extensions.

The abstract CA must be related univocally to the real phenomenon in its dynamics, each cell has to correspond to a portion of the space or surface (of the territory T) where the phenomenon evolves, so the time corresponding to a step of the transition function has to be fixed, the size of the cell has to be specified e.g., by the length of its edge, these constant values in time and space are called global parameters; P is the set of global parameters, it includes both physical and empirical parameters. The choice of some parameters is imposed by the desired precision of simulation where possible, e.g. cell dimension; the value of some parameters is deduced by physical features of the phenomenon, e.g. the parameter related to energy dissipation by turbulence: an initial physically sounding value is considered at the beginning of validation, such value is corrected in the phase of model validation on the base of the simulation quality by attempts, depending on comparison of *discrepancies between real event and simulation results. A methodology, based on Genetic Algorithms, was usually used for calibrating the parameters of our CA models (Iovine et al., 2005).*

Each characteristic, relevant to the evolution of the system and relative to the space portion corresponding to the cell, is individuated as a substate; the finite set Q of the states is given by the Cartesian product of the sets of substates: $Q=Q_1\times Q_2\times......\times Q_n$ *, e.g., some substates for a lahar model are the average altitude of the part of territory corresponding to the cell (substate altitude), the thickness of the lahar inside the "cell" (substate lahar thickness), the depth of erodible (unconsolidated) pyroclastic stratum of "soil of the cell" (substate pyroclastic stratum depth); the dynamics of the phenomenon is expressed by the variation of values of the substates for each cell in the successive steps of simulation. Note that features related to the third dimension may be expressed in terms of substates, it permits to develop two dimensions models, operating three-dimensionally in fact (Avolio et al., 2012).*

MCA have to account for phenomena, whose dynamics involves more interacting processes, sometime of different nature, e.g., loss of lahar energy because of erosion of the unconsolidated pyroclastic stratum of the "cell", loss of energy of the lahar in the "cell" caused by its turbolence. These interacting processes are called "elementary" processes of the CA and compose the transition function. This implies that the transition function has to be divided in parts, the "elementary processes", that are computed sequentially, each one involves the updating of the MCA substates.

The last extension of MCA are the "external influences", that account for kinds of input from the "external world" independent of local interactions (that cannot be reduced to local interactions) on some cells of the CA, e.g., the external influence "lava alimentation at the vents" is applied at each step only to the cells that correspond to vents, the value of the substate "lava quantity" is updated by adding to the previous value the lava quantity, that is considered to be discharged (in the case of simulation of a real event) in the cell during the time step or that is supposed to be discharged (in the case of simulation of a conjectured event) in the cell during the time step (Di Gregorio and Serra, 1999).

Simulations of flow-like landslides were performed by several versions of the MCA model SCIDDICA since 1987 for both subaerial and subaqueous debris/granular/mud flows (e.g., Barca et al., 1987; Avolio et al. 2008; Mazzanti et al., 2010; Avolio et al. 2013; Lupiano et al., 2014; Lupiano et al., 2015a; Lupiano et al., 2015b; Lupiano et al., 2015c; Lupiano et al., 2017). Simulations of primary and secondary lahars were performed by the MCA model LLUNPIY (Machado et al., 2014; Machado et al., 2015a; Machado et al., 2015b; Chidichimo et al., 2016).

LLUNPIY, SCIDDICA-SS3 and SCIDDICA-SS2 are our most advanced models (in the sense that they include the features of the previous models plus other new ones) for simulating flow-like landslides and lahars, they permit to simulate the erosion process unlike other models, that were used in lahar simulation: LAHARZ (e.g., Schilling, 1998; Muñoz-Salinas et al., 2009), TITAN2D (e.g., Sheridan, 2005; Williams, 2008; Córdoba et al., 2014)."

Chapter 3 reads as follows:

"*3 LLUNPIY/3r model for lahar simulation*

LLUNPIY (Lahar modelling by Local rules based on an UNderlying PIck of Yoked processes, "llunp'iy" means flood in the Quechua language) is a model for simulating secondary and primary lahars according to MCA methodology applied to complex system, whose evolution may be mainly specified in terms of local interaction. MCA features of SCIDDICA-SS3 (Avolio et al., 2013) and SCIDDICA-SS2 (Avolio et al., 2008; Lupiano et al., 2016; Lupiano et al., 2017) are inherited by LLUNPIY; LLUNPIY for secondary lahars is extensively defined in Machado et al. (2015b), here are reported only the features of the model, that were applied in the study cases (reduced version LLUNPIY/3r from SCIDDICA-SS2) so no external influence was considered, the LLUNPIY/3r, *simulation starts considering data for each cell related to the altitude (value of substate altitude, see Chapter 1.2), data related to the depth of erodible pyroclastic stratum of "soil of the cell" (value of the corresponding substate, see Chapter 1.2); data related to thickness of lahar, (value of the lahar thickness substate, see Chapter 1.2).*

A reliable reconstruction of the first phase of a real event of lahar permits to fix an "initial" moment, where it is possible to deduce the thickness of lahar in the territory, these data constitute the values of the substate "thickness of the lahar" in the first step of the simulation. In the case of simulation of the collapse of a dam, that produced a momentary pond, the thickness of lahar is deduced by the mixing of pond water with the matter of dam and part of the unconsolidated pyroclastic stratum below. Note that the lahar events in the Vascun Valley, that we simulate, don't involve the very first phase of water percolation and detachment subsequent to water inclusion (Machado 2015), because the collapse of temporary pond is abrupt; in the cases of past event, data permitted simulation of the phenomenon just in the phase of lahar. Furthermore in the simulation of real and hypothesized events, all the lahars end into the Rio Pastaza, so the last phase of lahar deposition is omitted and the viscosity of lahar may be considered constant for these particular cases."

In table 1 the physical and empirical parameters are described, but their unit of measurement and values are missing.

their unit of measurement were inserted

Table 1 - Physical and empirical parameters

Denotation	Description
p_r	cell **r**adius [m] (half the distance between the center of the central cell and the center of one of its adjacent neighbors)
p_t	**t**ime corresponding to a MCA step [s]
p_{cf}	**c**oefficient of **f**riction [-]
p_{dt},	energy **d**issipation due to **t**urbulence [-]
p_{pe} ,p_{de} , p_{tm}	**p**rogressive **e**rosion [-], energy **d**issipation due to **e**rosion [-], **t**hreshold of **m**obilization [m]
p_{Madh}, p_{madh}	**M**ax and **m**in **adh**erence [m]
p_{khl}	loss of kinetic head [m]

Then, how are these parameters calculated?

More specifications are added in "*Introduction*" and in "*3.1 Introduction to the LLUNPIY/3r version*"

In the Introduction:

“*The choice of some parameters is imposed by the desired precision of simulation where possible, e.g. cell dimension; the value of some parameters is deduced by physical features of the phenomenon, e.g. the parameter related to energy dissipation by turbulence: an initial physically sounding value is considered at the beginning of validation, such value is corrected in the phase of model validation on the base of the simulation quality by attempts, depending on comparison of discrepancies between real event and simulation results. A methodology, based on Genetic Algorithms, was usually used for calibrating the parameters of our CA models of surface flows (Iovine et al., 2005).*”

in 3.1 Introduction to the LLUNPIY/3r version

“*Physical parameters regard physical quantities that are used in equations of the transition function and correspond to values adopted in the implementation of the model (e.g. cell apothem, that depends on several factors, data precision, insuperable approximation limits related to specific features of the phenomenon) or values as the temporal correspondence of a CA step that must account that* $p_a/p_t>v_{mx}$ *where* v_{mx} *is the maximum possible velocity of flows during the development of the phenomenon, in other words the shift of a flow in a CA step hasn’t to overcome the neighborhood. All the parameters, except* p_a *and* p_t*, are empirically fixed in the phase of model validation by the simulation quality, initial values of parameters were deduced by the physical features of the phenomenon, e.g. a very slow lahar would emerge unbelievably in simulation by largest values of* p_{cf}*, the coefficient of friction and* p_{dt}*, the energy dissipation due to turbulence*”.

The substates should be describe more extensively and clearly (for example Q_{TH} in equation 1 is not indicated in table 2).

The substates have been now described in the revised manuscript:

“*Each characteristic, relevant to the evolution of the system and relative to the space portion corresponding to the cell, is individuated as a substate; the finite set Q of the states is given by the Cartesian product of the sets of substates:* $Q=Q_1\times Q_2\times......\times Q_n$ *, e.g., some substates for a lahar model are the average altitude of the part of territory corresponding to the cell (substate altitude), the thickness of the lahar inside the “cell” (substate lahar thickness), the depth of erodible (unconsolidated) pyroclastic stratum of “soil of the cell” (substate pyroclastic stratum depth); the dynamics of the phenomenon is expressed by the variation of values of the substates for each cell in the successive steps of simulation. Note that features related to the third dimension may be expressed in terms of substates, it permits to develop two dimensions models, operating three-dimensionally in fact (Avolio et al., 2012).*”

Q_{TH} and Q_{LT} denote the same substate, all the Q_{TH} were substituted by Q_{LT}. Thank you for catching the mistake.

“*Pyroclastic cover mobilization*
Soil features together with the quantity of water content determine a value p_{tm} *of mobilization threshold to be compared with the kinetic head* Q_{KH} *of lahar debris inside the cell, when* $Q_{KH} > p_{tm}$*, then the pyroclastic cover is eroded, the lahar thickness augments and altitude diminishes according to the following empirical formula, that turned out to be valid in different models of debris flow e.g. (Avolio et al., 2008), snow avalanche (Avolio et al., 2017) and primary and secondary lahars e.g. (Machado, 2015).*

$$-\Delta Q_D = \Delta Q_{LT} = -\Delta Q_A = (Q_{KH} - p_{tm})\cdot p_{pe} \,, \qquad (1)$$

There is correspondingly a dissipation of energy, proportional to the depth of erosion, it is specified by a decrease of kinetic head according to the following formula:

$$-\Delta Q_{KH} = (Q_{KH} - p_{tm}) \cdot p_{de} \ , \qquad (2)$$”

In equation 3, the effect of turbulence is considered. The latter is specified by means of the Reynolds number that depends on viscosity. I am surprised to not see in cinematic equation 8 a viscosity term depending on velocity. Could you clarify this point? Finally, what are the initial conditions to start a simulation?

These two points were clarified in different parts of the paper: no external influence was considered in LLUNPIY/3r simulations.

“*This “adherence” method was initially used for modelling lava flows by CA, in order to manage the continuous variation of viscosity by cooling of lava e.g., (Avolio et al., 2006). The approximation for accounting for viscosity inside a CA context can be intuitively explained as follows: instead of considering innumerable layers of fluid flowing over one another, at most two layers are considered, the first layer, whose maximum thickness (adh) is determined by the coefficient of viscosity, cannot move, if the thickness of fluid th overcomes adh, a second layer with thickness th-adh is considered to slide on the first one with a friction coefficient related to viscosity.*”

The simulation starts as follows:

“*A reliable reconstruction of the first phase of a real event of lahar permits to fix an “initial” moment, where it is possible to deduce the thickness of lahar in the territory, these data constitute the values of the substate “thickness of the lahar” in the first step of the simulation. In the case of the simulation of a lahar produced by the collapse of a dam holding a momentary pond, the thickness of lahar is deduced by the mixing of pond water with the dam material and part of the unconsolidated pyroclastic stratum below. Note that the simulated lahar events, occurred in the Vascun Valley, don’t involve the very first phase of water percolation and detachment subsequent to water inclusion (Machado 2015), since the collapse of temporary pond is abrupt; in the cases of past event, data permitted simulation of the phenomenon just in the phase of lahar. Furthermore in the simulation of real and hypothesized events, all the lahars end into the Rio Pastaza, so the last phase of lahar deposition is omitted and the viscosity of lahar may be considered constant for these particular cases.*”

2) The sections regarding the simulations (3.3 and 4.2) need some improvements. It seems that the model is calibrated on 2008 event and then validated with secondary lahar events of February 2005 and August 2008, but only the latter is shown.

Now data of both the events are reported, in particular for February 2005 event. A comparison with TITAN2D simulation is also reported.

“*3.3 LLUNPIY calibration and validation*

We selected the 2005 and 2008 lahars of Vascún Valley respectively for LLUNPIY/3r version calibration and validation. Available data, although incomplete, of the flood phase (Machado et al., 2015b) seemed promising in order to obtain reliable simulations. In fact data of different sources were carefully compared and analyzed (Williams et al., 2008; IGEPN, 2008) in order to reconstruct as accurately as possible the two events (Machado et al., 2014a and 2014b).

The simulation of 2005 event is based on a Digital Elevation Model (DEM) with 1m cell size (supplied to us by Dr. Gustavo Cordoba), while the 2008 lahar was performed with a DEM of 5m *cell size (supplied by IGEPN). In both cases a uniform thickness of 5 m was imposed for detrital cover, because detailed surveys were not available. This introduces a series of approximations that influence negatively the results of simulations. Such approximations can be reduced by an opportune survey of field data, e.g. by soil tomographies, MASW, coring, etc.*

The same set of LLUNPIY/3r parameters was used in the two cases except for the parameter of progressive erosion (p_{pe}*) because of different percentages of water in the soil. The 2005 event was triggered in a higher and very slope zone of Rio Vascún, when the water concentration in the soil, by rainfall, reached critical values. The 2008 event was dissimilar, because the breaking of a temporary pond released suddenly a larger water quantity (in comparison with 2005 case) with strong turbulence, whose effects correspond to a higher value of the parameter of progressive erosion (Machado et al., 2015b).*

The results of the simulations of 2008 event (Machado et al. 2015b) are extensively reported in this study since this event is very important because it was caused by a breaking of a temporary pond, the same typology of the phenomenon, whose development, we want to forecast. The reliability of results of the simulation in comparison with the real event permitted us to confide in the goodness of the method, the new simulations were performed with the same data precision and the same values of parameters.

Simulations of 2005 event were limited by the partial information of data field and DTM: we consider a stretch of about 2.3 km, from elevation 2150 m a.s.l., about 850 m upstream of El Salado Bath, to elevation 1900 m a.s.l. in correspondence of Pastaza River. The area, where our simulation starts, does not concern the detachment phase that occurs 8 km upriver. A kind of detachment, where an initial velocity of 7 m/s was imposed to lahar, was considered in order to express the first arrival of lahar flows. An equivalent fluid approach was adopted, because precise data about water flows are not available. Therefore, bulking must account not only for erodible layer, but for water inclusion. The total mass is inclusive of the water mass. This generates a discrepancy between the lahar volume, measured on the deposit and "fluid" lahar volume including water to be loss in the event last part.

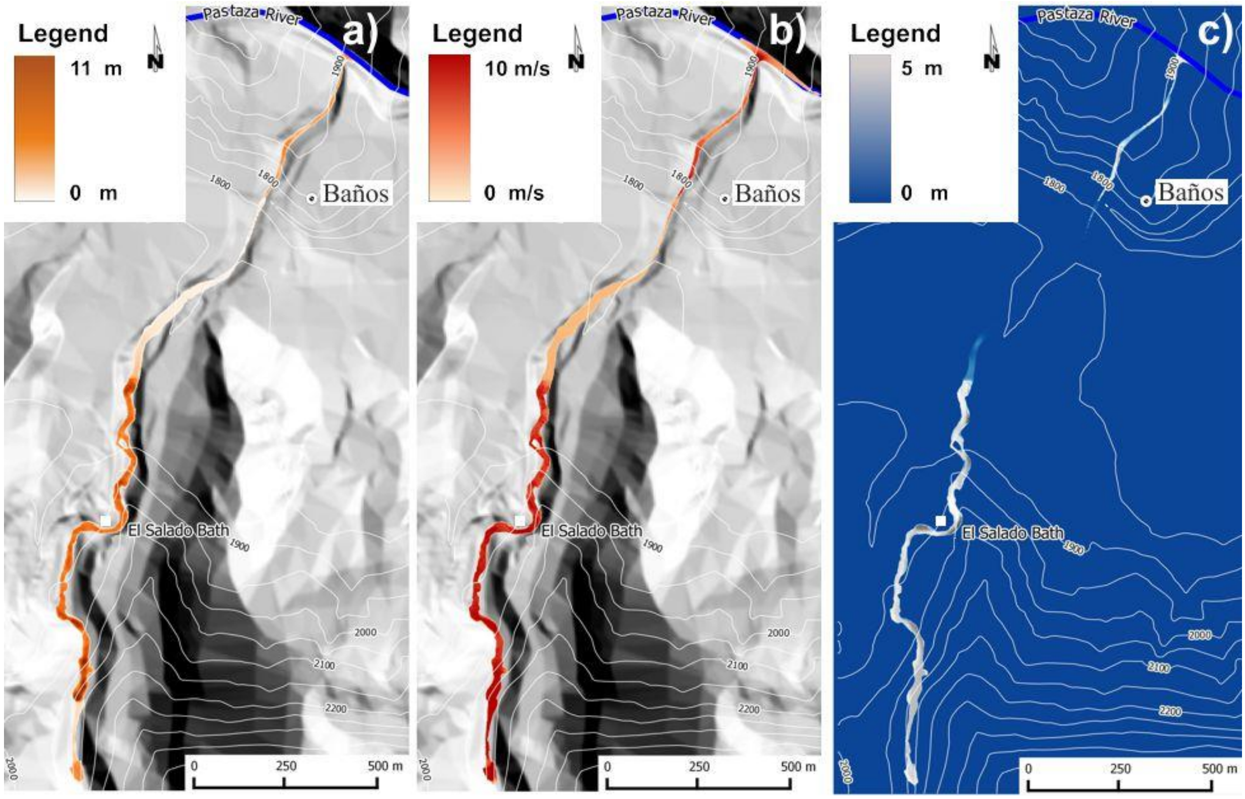

Figure 5: (a) Maximum thickness, (b) maximum velocity, and (c) erosion depth, in 2005 simulated event.

Fig. 5 shows the simulation developed with LLUNPIY in the considered sector. In particular, the maximum debris thickness values, which were reached by the lahar in simulation, are reported in Fig. 5a. Maximum velocities, reached by simulated flows (Fig. 5b), are high in steeper areas (the expected result) and decrease gradually at the outlet in downstream. A velocity increase occurs at south of Baños, probably because of the higher gradient of the river bed. Erosion has a trend similar to that of the velocity (Fig. 5c). Table 3 synthesizes values of Fig. 5 and compares such data with field data of IGEPN, reported in IGEPN 2005, and with simulation performed by Titan2D (Williams et al., 2008). Such field data are obviously partial for the complete development of catastrophic phenomenon, but extremely precious by comparison with our simulations. Observation data are not sufficient to a precise comparison with the simulation paths that are partial because limited field data. Furthermore, the lahar starts with null velocity in the simulation of (Williams et al., 2008), while LLUNPIY simulations start with 7 m/s velocities. The difference for total eroded mass rises from the lost water volume that was not possible to be considered in measurements.

The simulation of the 2008 lahar is shown in Fig. 6: the flow speed arrived up to 20 m/s in many areas of the valley, about 970000 m^3 *is the quantity of eroded material. The maximum height obtained in the simulated flow (Fig. 6a) is 22 m and has been reached in some sectors where the valley is particularly narrow, while the estimated average value by IGPEN (2008a and 2008b) is 4 m.*

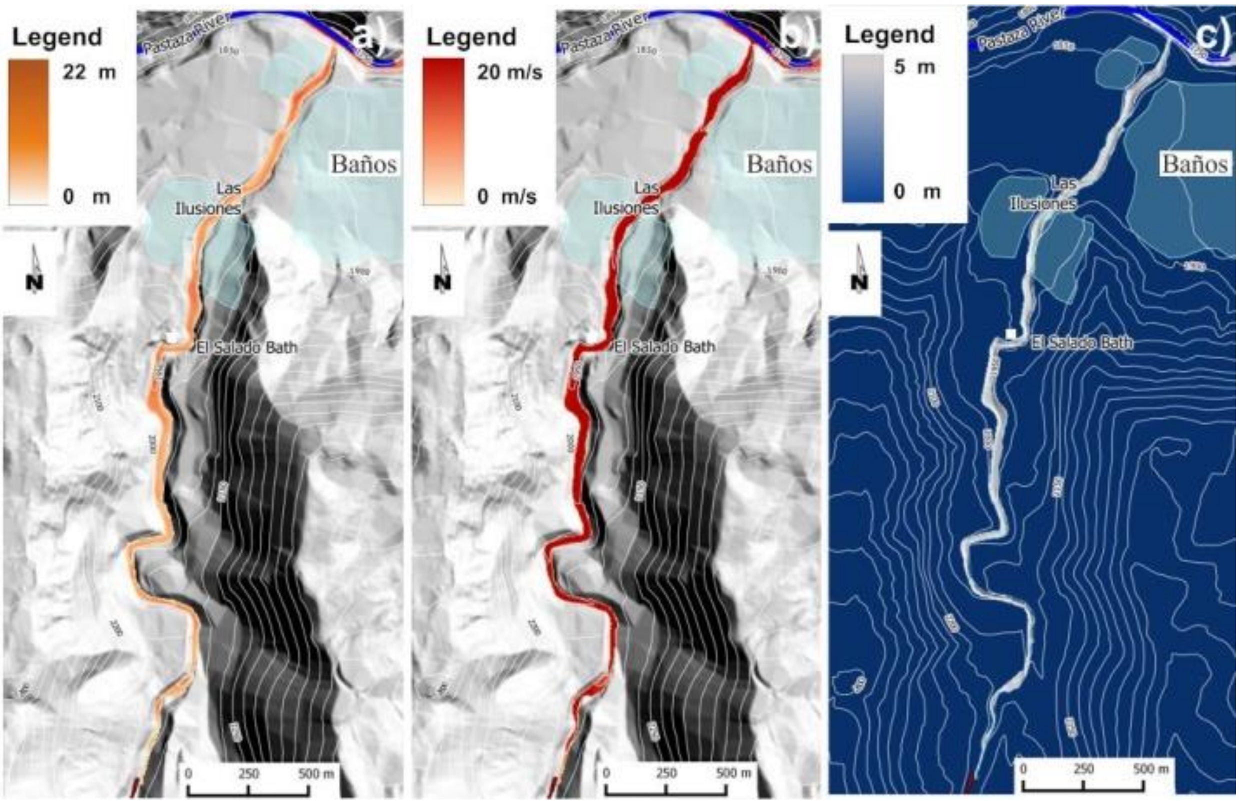

Figure 6: 2008 simulated event. a) Maximum thickness, b) Maximum velocity, and c) erosion depth.

Table 4 compares some data of simulation by LLUNPY with corresponding field data of IGEPN (2008). It is possible to note that the data deriving from the simulations are not many different from the known measured ones. The flow velocity of 15 m/s represents an estimated value, not measured.

These results demonstrate that LLUNPIY/3r is a reliable model, if we take into account that simulation are based on incomplete, sometime very approximate data concerning the pre-event and post-event, furthermore the inevitable errors in records related to this event have to be considered. Therefore an extension of LLUNPIY/3r is promising in order to introduce secondary features of the phenomenon to be tested. Simulations reproduce satisfactorily the overall dynamics of the events; there is a good matching between real and simulated lahar path, velocity and height of detrital flow; note that different approaches obtain always excellent results about the path because the lahar is canalized by steep faces."

Table 3 - Comparison among field data, Titan2D and LLUNPIY simulation data.

	Field data	*Simulations output Titan2D*	*Simulation output LLUNPIY/r3*
Mean velocity between Seismic Station and AFM	7 m/s	-	-
Mean Velocity between AFM and El Salado	3.10 m/s	-	-
Velocity at El Salado	3.1m/s	5.8–8.9. m/s	3.1 m/s
Velocity at final point (Las Ilusiones)	-	1.1–2.6 m/s	3 m/s
Time between AFM station and El Salado	16’	-	-
Time between start point and El Salado	-	-	6-7’
Time between El Salado and Las Ilusiones	-	-	14’
Total time between start point and Las Ilusiones	-	~8-14’	20’
Eroded debris between start point and El Salado	-	-	38000 m^3
Eroded debris between El Salado and Las Ilusiones	-	-	71000m^3
Total lahar volume between start point and Las Ilusiones	55000/70000m^3	50000/70000m^3	109000 m^3

Table 4 - Comparison between field and LLUNPIY simulation data

	Field data	*LLUNPIY output*
Maximum velocity	15 m/s	20 m/s
Velocity at El Salado	4.7 m/s	6 m/s
Time between start point and El Salado bath	5’	4’ 50”
Maximum flow between start point and El Salado	640 m^3/s	633 m^3/s
Total time between start point and Rio Pastaza	-	9’
Total eroded debris	-	970000m^3

“4.2 Preliminary hypotheses and results of simulations

LLUNPIY was calibrated and validated for secondary lahars by simulating two events of February 12, 2005 and August 22, 2008 in the Vascún Valley of Tungurahua Volcano in Ecuador (Machado et al., 2014; Machado et al., 2015b). In particular, the 2008 event is very important in order to confirm the value of the model parameters, tuned in the simulation even where the cause of the lahar was the breakdown of a temporary pond, generated by a small landslide. Those successful simulations permitted to be confident in the scenarios which could be realized by new simulations. Of course, a very accurate updating of geological data (DEM or DTM, detrital cover depth, etc.) and sufficient geophysical surveys are necessary for applications in order to mitigate the lahar risk.

An initial study was performed about the potentiality of applying mitigation measures in the Vascún Valley by triggering lahars of planned size (the lahar level is here considered as the relevant datum) through the controlled collapse of rudimentary ponds.

A preliminary analysis of the principal canyons of the Vascún Valley was performed in order to individuate favorable points for positioning embankments as dams; three points were chosen for building temporary dams: one located into Rio Vascún (point 1 in Fig. 9, Fig. 10, Fig.11 and Fig. 12), the second one located in a stream, tributary from the right (point 2 in Fig. 9, Fig. 10, Fig. 11 and Fig. 12), the third one located in a stream, tributary from the left (point 3 in Fig. 9, Fig. 10, Fig. 11 and Fig. 12). Rio Vascún in turn is tributary of much broader Pastaza River, where lahars of Vascún Valley disperse. Simulations concern the lahars generated in the points 1, 2 and 3 (Fig. 9, Fig. 10, Fig. 11 and Fig. 12), in short, lahar 1, 2 and 3. The same initial volume of 2008 event was selected for all the simulations except the last one. Three initial points permit to analyze an almost exhaustive set of possible conditions; we performed a sequence of simulations by LLUNPIY/3r, of course, with the same parameters values of the successful simulation of 2008 August 29 event. We present here some selected simulations, which look interesting for many considerations, which may be deduced by their analysis.

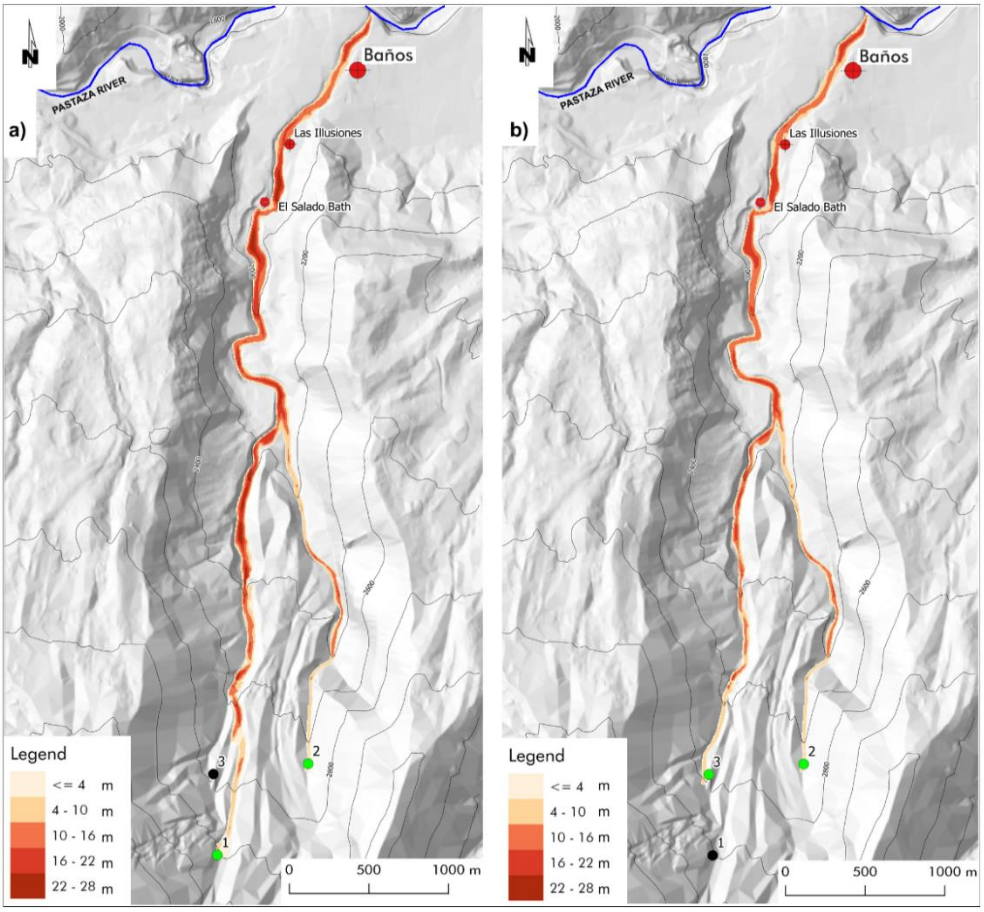

Figure 9: Simultaneous triggering of lahars from points 1 and 2 (a), from points 2 and 3 (b). The maximum thickness of the lahar during the conjectured events is reported in meters according the legend.

Initially, we considered two scenarios in order to investigate the effects of simultaneous and differed in time confluence of two lahars, the results of such simulations induced us to consider a larger set of cases. The former one is generated by the simultaneous triggering from the points 1 with 4875 m^3 *of detachment volume and 2 with 4500* m^3 *of detachment volume (Fig. 9a), the second one is generated by the simultaneous triggering from the points 2 with the same previous detachment volume and 3 with 4250* m^3 *of detachment volume (Fig. 9b). The confluence of the lahars in the Rio Vascún (for the following the confluence point) is almost simultaneous in the latter scenario, because of the similar distance between the triggering points and the confluence point; the situation is diverse for the former scenario, because the distances of the triggering points from the confluence point are very different. Intuitively the former case would be less dangerous, because the flood peaks of the two lahar cannot coincide at the confluence point, but the maximum thickness of lahar in the former scenario is 27 m., while the smaller value of 21 m. is detected in the latter scenario. The analysis of the two simulations showed that a very larger mass was eroded in the first part of the path from the point 1 in the former case. This unexpected result permits to plan an opportune strategy according to the degree of control for triggering lahars 1, 2 and 3 from the three respective points. If triggering can be well controlled with moderate/heavy rainfall, then the best choice is to trigger lahar 3 (smaller erosion) before lahar 1, so that lahar 3 anticipates part of the erosion process in the common path of both the lahars (1 and 3) as far as the confluence point and reduces consequently the thickness of the lahar 1. When the peak of the lahar 3 is gone beyond the confluence point, then the lahar 2 can be triggered before the lahar 1, which has to be generated as late as possible. Anyway, the last lahar to be triggered has to be surely lahar 1 but a further investigation needs in order to understand better the priority between lahar 2 and 3; the study of single lahars generated in the points 1, 2 and 3 could solve the question, as it may be deduced with the following simulations with triggering single lahars.*

Lahar 1 causes the maximum erosion, with a maximum thickness of 26 m., because it follows the path of Rio Vascún, that is the largest rio in the valley (with a larger volume of pyroclastic cover to be eroded), lahar 3 shares a relevant part of the previous path and reaches a maximum thickness of 19 m., while the lahar 2, whose path is less long before its late confluence into Rio Vascún, involves the smallest erosion (maximum thickness of 16 m). Such results solve the doubt that we put forward with the first simulations.

An operation of "cleaning" of pyroclastic cover could be projected by triggering initially lahar 2, with a first mobilization of the detrital cover as well for the area related to last part of the Rio Vascún from the confluence point of lahar 2 (maximum thickness 16 m, Fig. 10b); when the lahar 2 dissolve into Pastaza river, lahar 3 could be triggered with a first erosion of the detrital cover between the confluence points of the lahars 2 and 3 into Rio Vascún, its maximum thickness does not overcome 16 m, (Fig.10c), then the most dangerous lahar 1 of Rio Vascún could start at the exhaustion of lahar 3, minimizing the hazard; the maximum thickness before the confluence of lahar 3 into Rio Vascún doesn't overcome 22 m (Fig. 9a and Fig. 10a).

We tested successfully the outcomes of this strategy by simulating the triggering of the three lahars in successive times, each one immediately after the exhaustion of the previous one; the first phase concerns the lahar 2 (Fig.10b), the maximum thickness doesn't overcome 14 m in the last part of the path, from north of El Salado Bath to south of Baños.

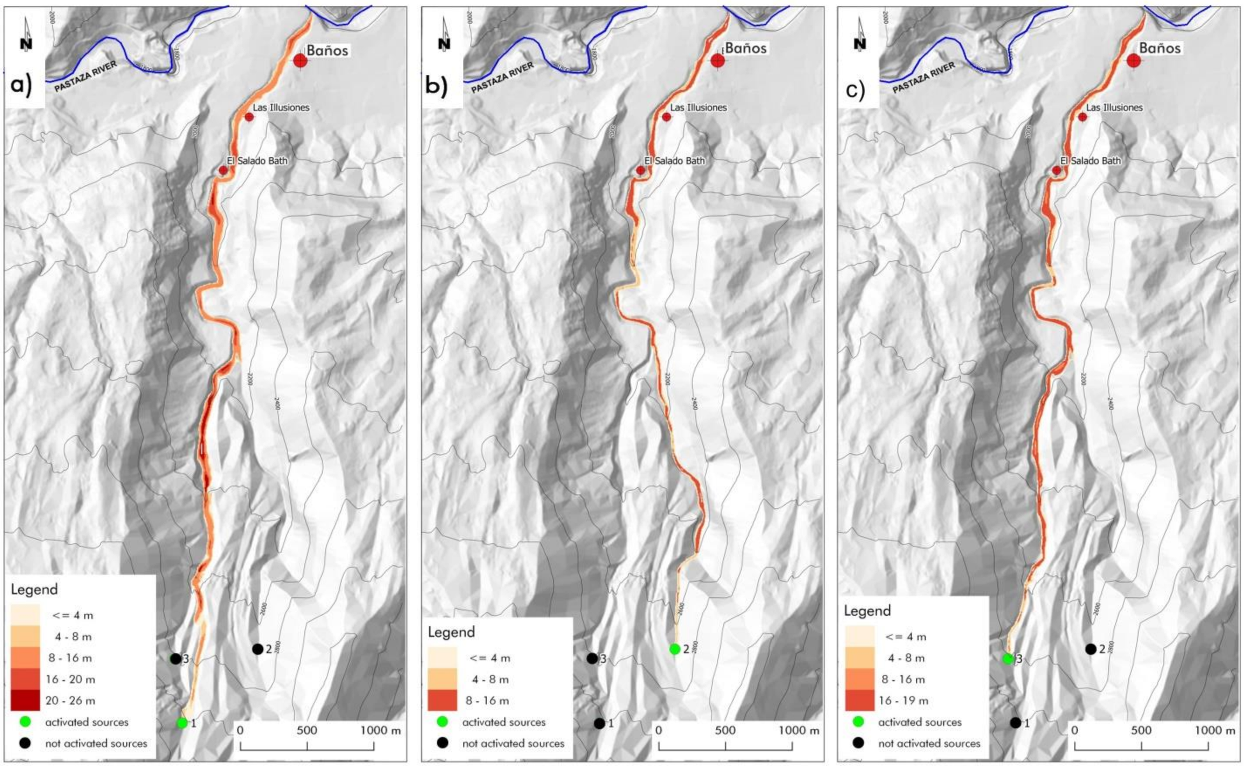

Figure 10: Single triggerings: lahar generated in point 1 (a), in point 2 (b) and in point 3 (c). The legend specifies the maximum thickness of the lahar reached during the conjectured events for each point (cell).

The erosion depth of pyroclastic cover after the lahar 2 exhaustion prevents that the maximum thickness of the successive lahar 3 overcomes 10-12 m after the confluence point with lahar 2 (Fig.11a) because of the reduced pyroclastic cover, while 19 m are reached with triggering only the lahar 3 (Fig.10c).

Finally, the most dangerous lahar 1 doesn't overcome 4-8 m in the inhabited zones (Fig.11b), while it reaches 26 m of maximum thickness in the last part of the path (Fig.10a), when the other lahars 2 and 3 are not generated.

This last result points out the importance of "cleaning" of pyroclastic cover according to an opportune strategy, which can be deduced by the outcomes of simulations, which explore all the possible significant cases.

Last simulations concern two cases of simultaneous triggering of all the lahars with the same detachment volumes from points 1, 2 and 3 of the previous simulations (Fig. 12a) and the double detachment volumes from the same points (Fig. 12b) in order to understand how triggering larger volume could increase the lahar dangerousness. Results show that the maximum thickness of the lahar in the former case (Fig. 12a) is 28 m, while the maximum thickness of the lahar in the latter case (Fig. 12b) is 29 m, just a meter more. A double initial volume does not involve much larger erosion in this context, the joint effect of a larger volume and erosion doesn't increase in dramatic way the hazard.

The overall results confirm the goodness of the strategy of triggering lahars at different times according to an accurate analysis of simulations after a precise knowledge of the geological features of the area of application. We remember that these simulations were obtained without sufficient data about the pyroclastic cover (it is obviously overestimated), that would have led to results with the desired precision, anyway, this problem doesn't compromise the reliability and validity of the proposed methodology.

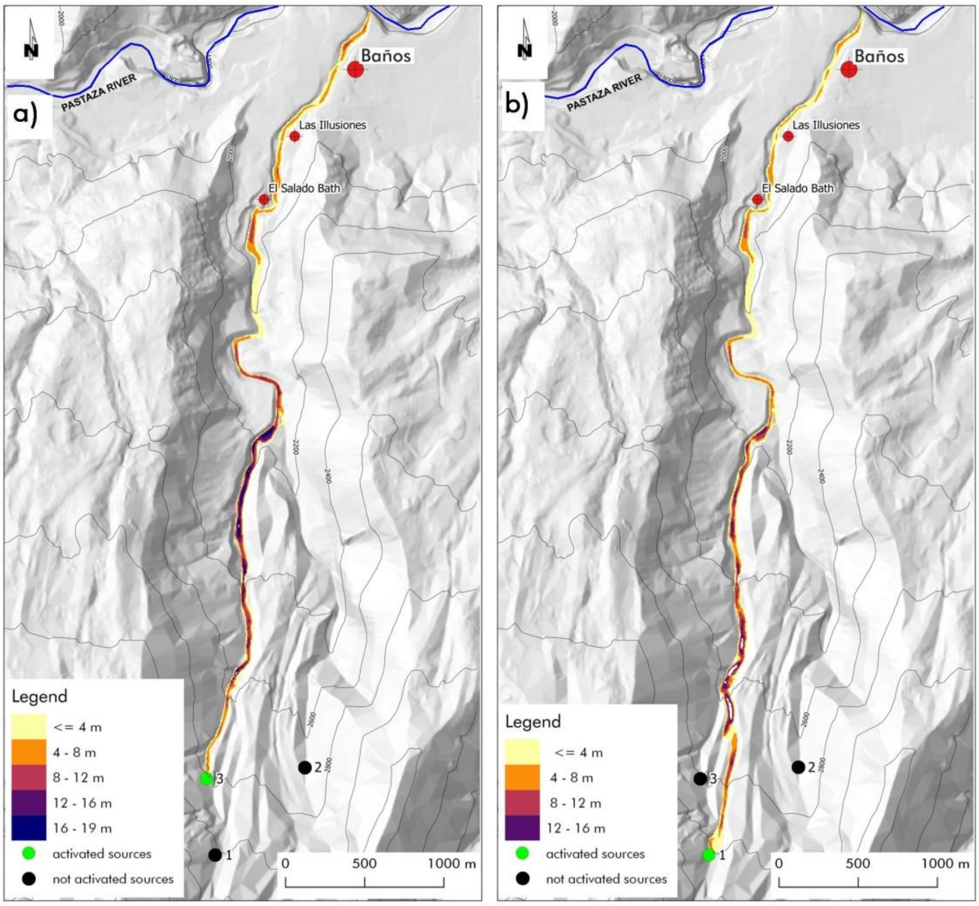

Figure 11: Simulations of deferred triggering of lahars generated in point 3 (a), and 1(b). The legend specifies the maximum thickness of the lahar reached during the conjectured events for each point (cell).

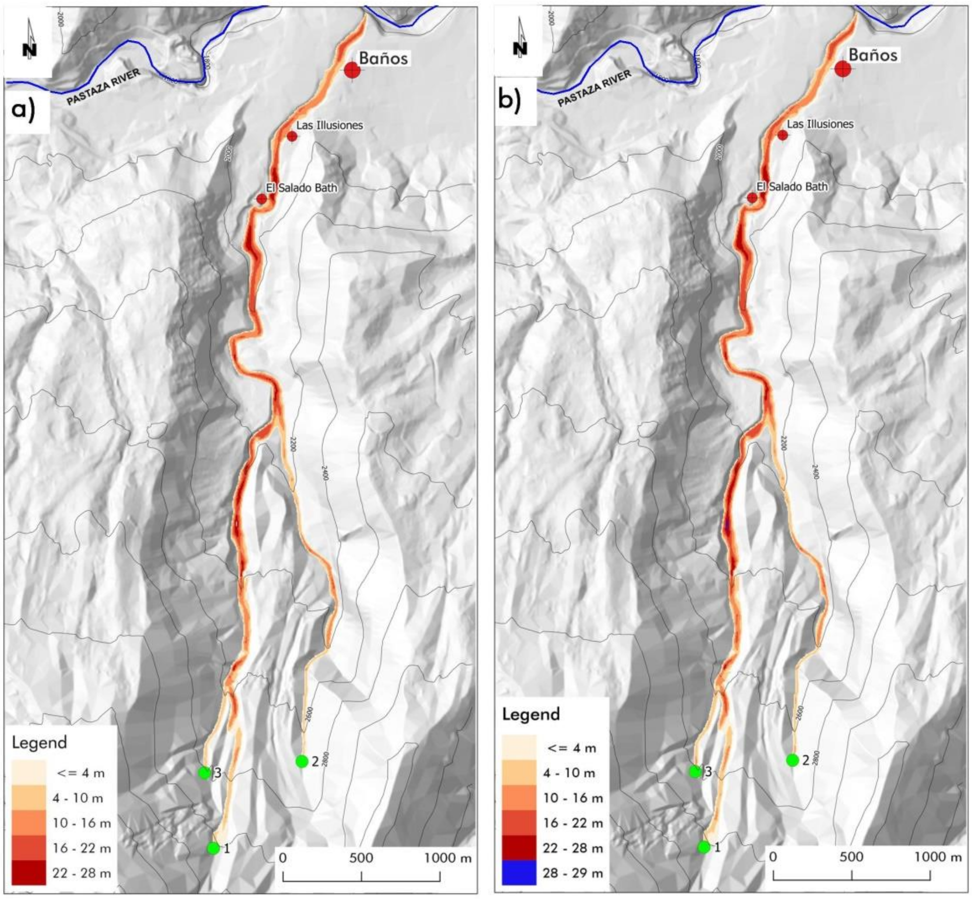

Figure 12: Simulations of simultaneous triggering of lahars generated in point 1, 2, 3. In (a) with total detachment volume of 13625 m3 and in (b) with total detachment volume of 27250 m3. The legend specifies the maximum thickness of the lahar reached during the conjectured events for each point (cell).

In table 3 some field data are compared, but regarding only the 2008 event used for calibration if I have not misunderstood. To me, these points should be clarified.

Please see the answer to the previous comment