SCIDDICA-SS_3: A New Cellular Automata Model for Simulating Fast Moving Landslides

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Abstract - *Cellular Automata (CA) are discrete and parallel computational models useful for simulating dynamic systems that evolve on the basis on local interactions. Some natural events, such as some types of landslides, fall into this type of phenomena and lend themselves well to be simulated with this approach. This paper describes the latest version of the SCIDDICA CA family models, specifically developed to simulate debris-flows type landslides. The latest model of the family, named SCIDDICA-SS_3, inherits all the features of its predecessor, SCIDDICA-SS_2, with the addition of a particular strategy to manage momentum. The introduction of the latter permits a better approximation of inertial effects that characterize some rapid debris flows. First simulations attempts of real landslides with SCIDDICA-SS_3 have produced quite satisfactory results, comparable with the previous model.*

Keywords: Cellular Automata, Modelling, Debris Flows, SCIDDICA.

1 Introduction

Many natural phenomena, like some complex fluid-dynamical phenomena, are difficult to be modelled through standard approaches, such as differential equations [1]. As a consequence, innovative numerical methods emerged from alternative computational paradigms such as Cellular Automata (CA), Neuronal Nets, Genetic Algorithms, etc. (cf. [2], [3], [4]).

It is worth to note that some natural events are difficult to be simulated by valid existing models at a "microscopic" or "mesoscopic" level since they generally evolve on very large areas, thus needing a "macroscopic" level of description. In this case, Macroscopic Cellular Automata (MCA) [5] can represent a valid choice for modelling and simulating these complex dynamical systems like fluid-dynamical natural phenomena. MCA are an extension of classical CA, and were developed in order to model many natural macroscopic events that seem difficult to be modelled in other CA frames, e.g. the Lattice Boltzmann method ([6],[7]), just because they take place on a large space scale. Debris flows, for example, fall in the category of surface flows that evolve on large-scales, and are natural candidates to be modelled through two-dimensional MCA.

In the last years, CA proved to be a valid alternative to differential equations in simulating some complex natural phenomena [8], [5]. In particular, attempts of simulating flow-type landslides have recently been carried out by several authors, also through CA models, with satisfactory results (e.g. [9], [10], [11], [12], [13]). Among these efforts, the SCIDDICA MCA model family was developed for simulating landslides of debris-flows type and were first applied for simulating the Tessina slow-moving earth flow [14]. MCA are also adopted for simulating other phenomena, such as different types of lava flows [15], pyroclastic flows [16], avalanches [17] and, in their latest application, to combined subaerial-subaqueous landslides [18].

SCIDDICA is a family of deterministic MCA models [19] for simulating the behaviour of landslides that can be typologically defined as "flows" [20]. This assertion allows us to exploit on one hand the fact that MCA of the SCIDDICA family are based on the equivalent fluid principle, formalized by Hungr [21], and on the other permits to consider an intrinsic property of MCA, that is that they are considered in terms of a-centric system, i.e. systems whose evolution can be described by considering mainly local interactions among their constituent "elementary" parts [22], a typical characteristic of flows.

In the present paper, the latest SCIDDICA-SS_3 hexagonal release of the model is described. This latest version derives from the need to improve the previous model, SCIDDICA-SS_2 [18], in order to better manage inertial effects. In SCIDDICA-SS_3, by adopting an empirical strategy, the inertial character of the flowing mass is translated into MCA terms by means of local rules. In general, all SS_x releases of the SCIDDICA family are an extension to combined subaerial-subaqueous flow-type landslides, with a new flows characterization by their mass centre position and velocity [18]. These characteristics have allowed for a more appropriate characterization of momentum, allowing even for the description of its components along the direction of motion.

While still undergoing a preliminary calibration phase, first simulation attempts by SCIDDICA-SS_3 were performed by taking into account a real case of debris flows, namely the subaerial-subaqueous event which took place near the lake of Albano (Central Italy) in 1997. In the following sections, the model description and produced results will be presented.

2 MCA for Surface Flows

For MCA modelling purposes [5], landslides can be viewed as a dynamical system that evolves within a limited portion of the space, tessellated into regular cells (e.g. square, hexagonal). A *state* is defined for each cell that describes the physical characteristics of the corresponding portion of space; in particular, in the MCA framework the *states* of the cell are decomposed in *substates*, or rather the *state* of each cell can be expressed by the Cartesian product of all the considered *substates*, where each *substate* represents a particular feature of the phenomenon to be modelled (e.g., the altitude, depth of soil cover, thickness of landslide debris, landslide energy). *Elementary processes* constitute the *transition function* (τ) of the model: this is composed of a set of rules which describe *local processes* constituting the overall phenomenon. In addition, some *parameters* (e.g. the temporal MCA clock, cell dimension, etc) are generally considered, which allow to "tune" the model for reproducing different dynamical behaviours of the phenomenon of interest, by taking into consideration their physical/empirical meaning. At the beginning of the simulation, cell *states* are initialized by means of input values (e.g., through matrixes). Model *parameters* have also to be assigned in this phase. By simultaneously applying the *transition function*, τ, to all cells and at discrete steps, *states* are changed and the evolution of the phenomenon can be simulated.

Natural macroscopic phenomena, which evolve by generating flows of material and involving surface-flows can be modelled through two-dimensional MCA, because the third dimension (i.e., the height) can be managed as a property of the cell (i.e. a *substate*). Thus, it is possible to consider characteristics of the cell (i.e. *substates*), typically expressed in terms of volumes (e.g. debris volume), here in terms of thickness. This simple assumption permits to adopt an efficacious strategy, by means of the *Minimization Algorithm of the Differences* [5] (*Minimization Algorithm* in the rest of the text), based on the hydrostatic equilibrium principle, in order to compute outflows of material (e.g. debris in the case of landslides) from a central cell to the neighbouring ones.

3 The SCIDDICA-SS_3 MCA Model

As already mentioned, SCIDDICA is a family of deterministic MCA models, with hexagonal cells, specifically developed for simulating flow-type landslides. The SCIDDICA family includes many versions developed in previous years, from the first release [14], named *T*, to the latest SCIDDICA-SS_2 [18]. This development is also due to a continuous refinement of the adopted approach, which has furthermore given rise to a more physical modelling framework with the development of the SCIDDICA-SS_3 model. The model's transition function latest improvements include a better management procedure for inertial effects which characterise rapid debris flows. In fact, a first attempt of the introduction of momentum was made in an earlier version, named SCIDDICA-S_4 [23], but the lack of explication of the mass centre did not allow to exploit the full potentiality of the model and was soon abandoned. As a matter of fact, the introduction of the mass centre (or barycentre) in the SS*x* models has allowed a better approximation of the phenomenon from the physical point of view, so to allow to compare the SCIDDICA-SS_x model with other well-known debris flows models [24]. For instance, a test has regarded the comparison of simulation results of the 1997 Lake Albano (Lazio Region, Italy) debris flow carried out by SCIDDICA-SS_2 and the well-known DAN3D [25] software. Results achieved by DAN3D and SCIDDICA-SS_2 were surprisingly similar in terms of areal debris distribution, velocity and propagation time [24].

The SS_x releases have been implemented both for the need to simulate combined subareal-subaqueous landslides and to make velocity explicit, a methodological approach firstly applied to lava flows [26], [27]. The precedent release of the SS_x SCIDDICA family overcomes a typical restriction of many CA models, including Lattice Boltzmann [6] ones: a fluid amount moves from a cell to another one in a CA step, which corresponds usually to a constant time. This implies a constant local "velocity" in the CA context of discrete space/time. Nevertheless, velocities can be deduced by analyzing the global behaviour of the system in time and space. In such models, the flow velocity emerges by averaging on the cell space (i.e. considering clusters of cells) or by averaging on time (e.g. considering the average velocity of the advancing flow front in a sequence of CA steps). Therefore, in SCIDDICA-SS_x models, with the introduction of the coordinates of mass center of flows and the calculation of their movement, the velocity has been made explicit.

Moreover, in the SS_3 version, a new empirical strategy has been introduced for the determination of outflows from a cell towards its adjacent cells (the other cells of the neighbouring); such a strategy, intuitively discussed later on before its formalisation in section 3.1, has permitted to improve significantly the precision in the complicated computation of momentum for the flowing masses in the MCA context, where a macroscopic view was adopted.

The starting point is the *Minimization Algorithm*, where outflows from a cell are computed in order to obtain hydrostatic equilibrium in the neighbouring. In a cell, inflows and mass inside are composed as quantity, mass centre, kinetic energy and momentum. Momentum introduces an alteration of hydrostatic equilibrium, which is translated in terms of the *Minimization Algorithm* by modifying fictitiously altitudes of adjacent cells: altitude is opportunely lowered/raised according to the module and direction of momentum.

Then, the computation proceeds by two stages:

a) outflows toward the neighbouring cells are computed in the condition of different altitude alterations: this represents the situation of flows that just can overcome obstacles, neglecting other interactions;

b) the part of mass that cannot overcome obstacles is considered to interact strongly with such obstacles, in a complicated play of hitting and bouncing, where momentum disappears and part of kinetic energy is lost. Because of lack of directionality and by considering the remaining kinetic energy, the *Minimization Algorithm* is again applied with identical altitude variation (proportional to residual kinetic energy) in the adjacent cells. This permits to compute outflows toward cells penalized by the direction of momentum in the previous stage.

Substate	***Meaning***
Q_a	Altitude (in meters)
Q_{th}	Thickness of landslide debris (in meters)
Q_d	Maximum depth of detrital cover that can be transformed by erosion in landslide debris, it depends on the type of detrital cover (in meters)
Q_o (Q_i)	Debris outflow (inflow) (in meters)
Q_E	Total Energy of landslide debris (in joule)
Q_{px}, Q_{py}	Represent indicators of the momentum of the landslide debris, along the outflow velocity directions (in *kg m/s*)
Q_x, Q_y	Coordinates of the debris barycentre with reference to the cell centre (in meters)
Q_{kh}	Debris kinetic head (in meters)
Q_{oe} (Q_{oi})	Part of debris flow, the so called “external flow” (“internal flow”), normalised to a thickness, that penetrates the adjacent cell from central cell (that remains inside the central cell) (in meters)
Q_{XE}, Q_{YE} (Q_{XI}, Q_{YI})	Coordinates of the external flow barycentre (internal flow barycentre) with reference to the adjacent cell centre (in meters)

Table 1. SCIDDICA-SS$_3$: list of considered substates.

3.1 Formal definition of SCIDDICA-SS$_3$

The release SS$_3$ of SCIDDICA is formally defined by the quintuple:

$$\text{SCIDDICA-SS}_3 = <R; X; Q; P; \tau>$$

where:

- $R = \{(x, y) \in Z^2 \mid -l_x \le x \le l_x, -l_y \le y \le l_y\}$ identifies the hexagonal cellular space where the phenomenon evolves; Z is the set of the integer numbers;
- $X = \{(0, 0), (1, 0), (0, 1), (0,-1), (-1, 0), (-1, 1), (1,-1)\}$ is the geometrical pattern of the neighbourhood of the cell, Fig.1, given by the “central” cell and its six adjacent cells;

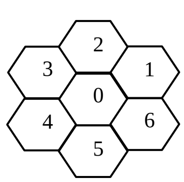

Fig. 1: The neighbourhood adopted in SCIDDICA-SS3. Key: the central cell is individuated by the index “0”; indexes 1–6 identify the cells of the neighbourhood.

- $Q = Q_{X1} \times Q_{X2} \times \ldots \times Q_{Xn}$ is the finite set of states given by the Cartesian product of the sets of the considered substates (Table 1). The value of the substate x in the cell is expressed by $q_x \in Q_x$. In the following, q_x indicates the values of a substate Q_x. When substates need the specification of the neighbourhood cell, the neighbour index is indicated between square brackets;
- P is the set of the global parameters [18] (e.g., the side of the cell, the temporal correspondence of a step of SCIDDICA-SS$_3$, etc) which account for the general frame of the model and the physical characteristics of the phenomenon (e.g., activation threshold of the mobilization, energy dissipation parameter);
- $\tau : Q^7 \rightarrow Q$ is the deterministic transition function for the cells in R.

At the beginning of the simulation (for $t=0$), the states of the cells in R must be specified, defining the initial configuration of the MCA. Initial values of the substates (Table 1) are initialized as follows:

– Q_a is set to the cell altitude a.s.l. (bedrock elevation plus depth of soil cover); in the landslide source, the thickness of the landslide debris is subtracted from the morphology;

– Q_{th} is zero everywhere – except for the source area, where the landslide debris thickness is specified;

– Q_E is zero everywhere – except for the source area, where it is equal to the potential energy of the landslide (with reference to the cell altitude);

– Q_d is the depth of the soil cover, which can be eroded by the landslide along the path;

– All remaining substates are set to 0 everywhere.

The transition function τ is applied, step by step, to all the cells in R, and the MCA configuration changes obtaining the evolution of the simulation.

3.2 Main characteristic of transition function τ of SCIDDICA-SS$_3$

Since SCIDDICA-SS$_3$ inherits all the features of the transition function of the previous model, this paper briefly describes the elementary processes of SS$_3$, τ_{SS3}, that are unchanged compared to SS$_2$, τ_{SS2}. For more details on SS$_2$, see [18], while new features are better herein described. In the following, (τ_{SS2}, τ_{SS3}) indicates the SS$_3$ elementary processes that have undergone slight changes (or none) with respect to SS$_2$, whereas (τ_{SS3}) indicates the new SS$_3$ elementary processes.

Mobilisation effects (τ_{SS2}, τ_{SS3}): An empirical strategy has been developed to better simulate the partial erosion of the regolith along the path of the landslide. In practice, when the kinetic energy overcomes an opportune threshold, then a mobilisation of the detrital cover occurs proportionally to the quantity overcoming the threshold. All heights q_a, q_r, and q_{th} and relative energies q_{kh} and q_E are updated as soil is eroded.

Computation of debris outflows (τ_{SS3}): Outflows from the central cell towards the neighbouring ones are computed by applying the *Minimization Algorithm of the Differences* ([5], [26]). The algorithm is based on the following assumptions:

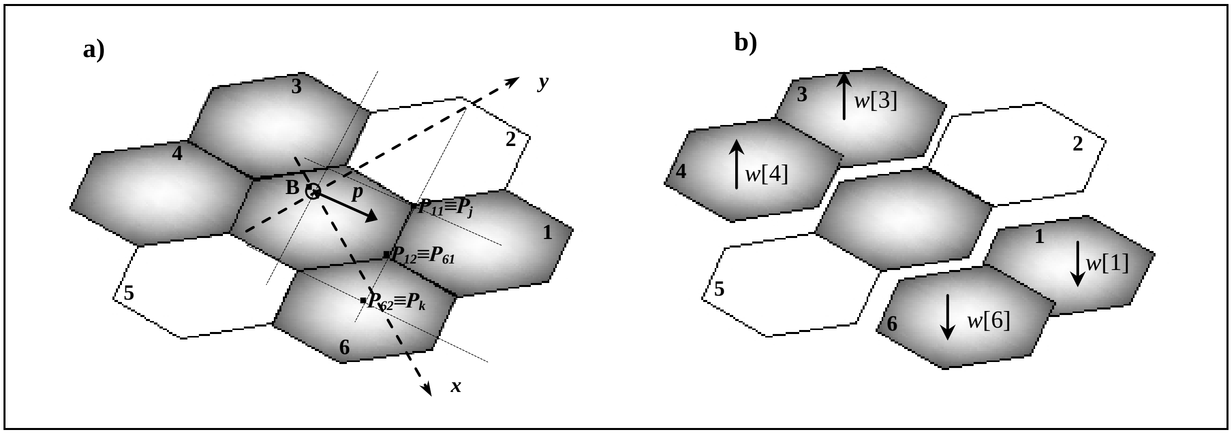

Fig. 2: An example of cell elevation alteration for emphasizing inertial effects. Shaded coloring indicate cells (numbered 1 through 6) affected by the procedure. (**a**) B is the barycenter of the mass inside a generic central cell with momentum module *p*. Segments $|P_{i(n)}P_{i(n+1)}|$ are determined by $|P_{11}P_{12}|$ and $|P_{61}P_{62}|$ for cells 1 and 6, respectively; (**b**) In the first phase of distribution step, the elevation of cells 1 and 6 are decreased of a quantity *w*[1] and *w*[2] respectively, while elevations of cells 3 and 4 are increased by the same quantities.

– In the central cell, an unmovable amount, $u(0)$, and another one which can be distributed to the neighbours, *m*, are in general considered, which is computed as:

$$m = \sum_{i=0}^{6} q_o[i]$$

where $q_o(i)$ is the flow towards the cell *i* and $q_o(0)$ is the part of *m* which remains in the central cell

– The content of the adjacent cells, $u(i)$ (i = 1,2, ... ,6), is considered unmovable.

Aiming at emphasising inertial effects of rapid debris flows, in the release SS_3, some directions are privileged according to the momentum of the debris inside the cell. In this regard we consider (d_x,d_y) the directional components of the velocity of outgoing flows from one cell and applied at the corresponding center of mass (Fig. 2a). Along the directions (d_x, d_y) it is possible to compute the two indicators (q_{px}, q_{py}) of the momentum given in module as:

$$p = \rho A q_{th} \sqrt{2 g q_{hk}}$$

where ρ is the density of the material of the landslide, *A* is the area of the cell, q_{th} the thickness of debris in a cell, *g* the gravity acceleration and q_{kh} the kinetic head of the landslide. By means of simple conventional geometric processes (cf. Fig. 2a), the segments $\overline{P_{i(n)}P_{i(n+1)}}$ are identified, where *i* refers to the neighboring cell *i* and proportionally to these segments, the amount of motion is "distributed", in module, to the neighboring cells according to the formula :

$$p_i = \frac{p \times \left|\overline{P_{i(n)}P_{i(n+1)}}\right|}{\left|\overline{P_j P_k}\right|}$$

where p_i indicates the part of the momentum which is "transferred" in the cell *i*, $\left|\overline{P_{i(n)}P_{i(n+1)}}\right|$ the length of the segment corresponding to the cell *i* and, at last, $\left|\overline{P_j P_k}\right|$ is the total length of the segment that goes from P_j to P_k (Fig. 2a). The cells towards which $p_i \neq 0$ are considered as *privileged* ones, as mentioned previously. Within the context of the hexagonal cellular space, along these latter the effect of momentum has to be stronger in order to account for the inertial properties of the debris flow. By definition, if for instance $p_i > p_j$, the direction towards cell *i* is the most privileged.

With the aim of privileging the directions defined by the various p_i, in SCIDDICA-SS_3 the heights (i.e., cell altitude plus landslide thickness) of the neighbouring cells are increased by an amount $w[i]$, (i=1, 2, ... , 6), computed as follows:

- $w[i] = -\alpha p_i$, for neighbour cells *i* which have $p_i \neq 0$, where α is a proportionality coefficient of kinetic energy (Fig 2b);
- $w[i] = \alpha p_i$, for cells opposite to cells with $p_i \neq 0$;
- $w[i] = 0$ for cells not involved in the motion (Fig. 2b).

In such a way, the *Minimization Algorithm* will privilege, in the distribution of the landslide debris, those cells whose heights are most decremented.

According to the previous considerations, an empirical double-phase strategy was developed in SS_3 to account for the inertial effects of rapid debris flows. In the first phase, inertial outflows $(q_0{}'[i])$ are first computed, introducing a sort of "weakening" of privileged senses. The *Minimization Algorithm* is applied in the following form:

$$m = q_{th}[0] - p_{adh}$$
$$u[0] = q_a[0] + p_{adh} + q_{kh}$$
$$u[i] = q_a[i] + q_{th}[i] + w[i]$$

where p_{adh} represents the water/air parameter of the adherence value (i.e. unmovable amount of debris in a cell).

The debris thickness remaining into the central cell is accordingly reduced to the value:

$$new\_q_{th}[0] = q_{th}[0] - \sum_{i=1}^{6} q_0^{'}[i]$$

while for the receiving cell *i*:

$$new\_q_{th}[i] = q_{th}[i] + q_0^{'}[i]$$

This phase obviously involves also the update of the energy new_q_E and new_q_{kh}, for both the central and neighbor cells *i* receiving a flow.

In the second phase, by considering the eventual residual debris, new_q_{th}, (i.e. the debris not distributed during the first phase) and kinetc energy, $new\_q'_{kh}$, (i.e. the kinetic energy decreased by the only outflows contribution), not-inertial outflows ($q_0^{''}[i]$) in the cell are computed, assuming the inertial effect to be negligible. The *Minimization Algorithm* is now applied in the following form:

$$m = \left[q_{th}[0] - \sum_{i=1}^{6} q_0^{'}[i] \right] - p_{adh}$$
$$u[0] = q_a[0] + p_{adh} + new\_q'_{kh}$$
$$u[i] = q_a[i] + \left(q_{th}[i] + q_0^{'}[i] \right)$$

At the end of the two phases, the total outflows $q_0[i]$ for each cell *i* of the neighbourhood can be determined as follows:

$$q_0[i] = q'_0[i] + q''_0[i]$$

while the final debris in the cell 0 is:

$$new\_qth = qth - \sum_{i=1}^{6} q_0^{'}[i] - \sum_{i=1}^{6} q_0^{''}[i]$$

increased by the sum of the incoming flows, in the central cell 0, of the two kinds of flows determined in the previous two phases.

Shift of the Outflows (τ_{SS2}, τ_{SS3}): The shift of the outflows is computed for both loops of the same computational step, according to a simple kinetic formula which depends whether the flow is subaerial or subaqueous (as for SS_2) [18], [26], [27]. In particular, the shift formula for subaqueous debris considers also the water resistance, using modified Stokes equations with a form factor that is proportional to mass.

The substantial difference with SCIDDICA-SS_2 is the calculation of the displacement in the first loop; in fact, at this stage the shift is calculated considering a variation of the height given by the values of $w[i]$, previously described.

The movement of flows affect the determination of the computation of the new co-ordinates of the barycentre, that is calculated as the weighted average of q_x and q_y, considering the remaining debris in the central cell, the internal flows and the inflows, at the end of the two loop phases.

Turbulence Effect (τ_{SS2}, τ_{SS3}**)**: A total energy reduction, besides the computation of the new total energy amount (new_q_E) in a cell, is considered by loss of flows, while an increase is given by inflows; moreover, the new value of the kinetic head (new_q_{kh}) is deduced from the computed kinetic energy and energy dissipation computed over the kinetic head, was considered as a turbulence effect

Obviously, updates of the total and kinetic energy are carried out at the end of the two phases of a step, that is, after the double distribution of the debris.

Air-Water Interface (τ_{SS2}, τ_{SS3}): Air-water interface is managed only for external flows from air to water and not vice versa. An external flow from an air cell (altitude higher than water level) to water cell (altitude lower than water level) implies always a loss of matter (water inside debris and components are lighter than water) proportional to debris mass, specified by an opportune parameter, implying a correspondent loss of kinetic energy, determined by kinetic head decrease.

4 SCIDDICA-SS_3 Applications

SCIDDICA-SS_3 was calibrated against the 1997 Albano lake (near Rome, Italy) event (Fig. 3a), which is a case of combined subaerial-subaqueous debris-flow [28]. This landslide occurred in the eastern slope of the Albano lake on the 7th of November 1997 after an intense rainfall event (128 mm in 24 hours), and began as a soil slide, mobilizing about 300 m^3 of fluvial material. The mobilized mass was channeled within a steeply dipping impluvium (about 40°) and thus evolved as a debris flow which entrained a large amount of debris material along the bottom of the channel and reached an estimated volume of some thousands of cubic meters at the coastline. A few amount of material was deposited at the coastline, while a greater quantity entered in water generating a little tsunami wave. Simulations permitted to verify the general model and to calibrate adequately its parameters.

In order quantitatively evaluate the simulation outcomes, experiments are compared with real cases by considering the following indicator e_1:

$$e_1 = \sqrt{\frac{R \cap S}{R \cup S}}$$

where *R* is the set of cells affected by the landslide in the real event and *S* the set of cells affected by the landslide in the simulation. The fitness function, e_1, considers a normalised value between 0 (complete failure) and 1 (perfect simulation). Simulations are judged “acceptable” only when the indicators show values not exceeding pre-fixed thresholds of acceptability, fixed on the base of empirical considerations (as commonly performed in statistical analysis). In the case of the Albano landslide, such value is considered as 0.7. The simulation carried out with the SS_3 model, and here presented (Fig. 3a, 3b, 3c) has a value of e_1 equal to 0.82, which represents a very good, though preliminary, result.

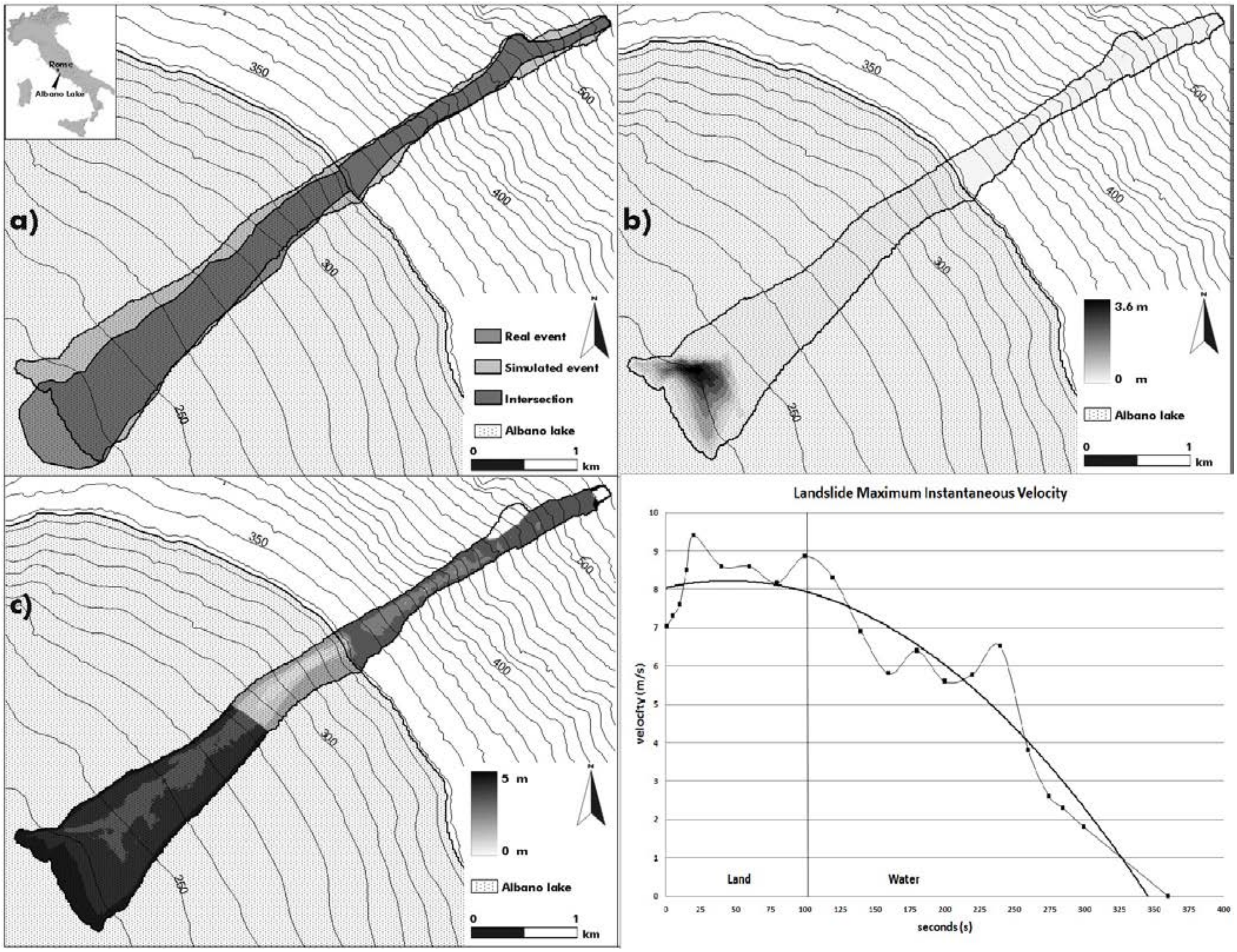

Fig. 3: The 1997 Albano lake subaerial-subaqueous debris flow. (a) Intersection between real and simulated event; (b) Deposit thickness; (c) Erosion depth; (d) Maximum instantaneous velocity. Results refer to the best performed simulation. The thick contour line represents the water level.

The simulation made with SCIDDICA-SS_3 is quite similar to that made with the previous model [18], both with regard to the areal extent (Fig. 3a) and concerning the mass of mobilized material, which has decreasing thickness values from the release area until the beginning of accumulation zone (Fig. 3b) and, finally, even as regards the thickness of eroded soil during the passage of the landslide (Fig. 3c).

The substantial difference that emerges comparing the simulation carried out with SS_3 with the one made with the SS_2 model is the management of the landslide detachment area. In fact, in the SS_3 model the emptying effect of the detachment area is rather quick, contrarily to what occurred in the SS_2 model, where this area was unable to completely empty until the end of the simulation, showing as a result less compact landslide front. Another difference, emerged from the comparison, is the speed of the landslide which decreases in SS_3. In fact, the velocity values that emerge from the simulation made with SS_3 (Fig. 3d), though slightly different from those obtained with the model SS2 [18], can be considered quite consistent with the real case.

Further refinements of the parameters could lead, therefore, for a better fitness as well as to speed up the propagation times.

5 Conclusions and future outlooks

SCIDDICA-SS_3 seems to capture fundamental instances of modeling surface flow with regards to conservation laws of physics according to a less empirical approach. Results of first simulations are satisfying, even if more controls and applications to different cases need and parameters must be better tuned.

Future research work is planned: coupling of different elementary processes must be improved, parameters have to be introduced independently from CA time step and cell dimension by an opportune formulation of the transition function.

Such future research will permit to extend such a methodology to other phenomena involving surface flows as snow avalanche, pyroclastic flows, soil erosion and coastal erosion.

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