

# Application context of the SCIDDICA model family for simulations of flow-like landslides

M.V. Avolio<sup>1</sup>, S. Di Gregorio<sup>1</sup>, V. Lupiano<sup>2</sup>, P. Mazzanti<sup>3</sup>, and W. Spataro<sup>1</sup>

<sup>1</sup>Department of Mathematics, University of Calabria, Rende (CS), Italy

<sup>2</sup>Department of Earth Sciences, University of Calabria, Rende (CS), Italy

<sup>3</sup>NHAZCA S.r.l. and Department of Earth Sciences, University of Rome “La Sapienza”, Rome, Italy

**Abstract:** Cellular Automata (CA) are parallel computing models whose evolution is governed by purely local laws. The global dynamics of complex systems simulated by means of CA emerges from the local interactions of their elementary components. Some macroscopic natural phenomena are included in the class of such complex systems. Among them, of particular interest are several types of “surface flows”, where typical examples are debris flows and lava flows. In this review paper, a methodology for modelling complex natural systems through Macroscopic Cellular Automata (MCA) is presented and applied to flow-type landslides simulations. Specifically, we will show the SCIDDICA family models, with particular reference to the hexagonal release of MCA models for the simulation of flow-type landslides. The models, here presented, are initially adopted for subaerial flow-like landslides simulations, and applied recently to combined subaerial-subaqueous flow-like landslides.

**Keywords:** Cellular Automata, Modelling, Debris Flows, Simulation.

## 1 Introduction

Many complex fluid-dynamical phenomena are modelled by Cellular Automata (CA) [1]. Lattice Gas Automata [2] and Lattice Boltzmann [3] models are particularly suitable for modelling phenomena at a microscopic scale. However, many natural phenomena are difficult to be modelled at such scale, as they generally evolve on very large areas, thus needing a macroscopic level of description. Moreover, they may also be difficult to be modelled through standard approaches, such as differential equations [4]. In this case, Macroscopic Cellular Automata (MCA) [5] can represent a valid choice for modelling and simulating complex dynamical systems like fluid-dynamical phenomena. MCA were proposed by Crisci and Di Gregorio for the first time in 1982 to model the dynamics of macroscopic spatially extended systems, and firstly applied to the simulation of basaltic lava flows [6]. Afterwards, MCA were adopted for the simulation of diverse macroscopic natural phenomena, such as other kinds of lava flows [7], debris flows [8], pyroclastic flows [9], traffic control [10] and, in their latest application, to combined subaerial-subaqueous landslides [11]. This review paper presents a MCA methodology that

has been successfully used for efficient simulations of natural complex phenomena, such as lava flows and pyroclastic flows for volcanic eruption and debris, mud, granular flows for landslides, with the SCIARA, PYR, and SCIDDICA [12] models, respectively. The aim of these models is to reproduce the dynamics of the phenomena of interest with the highest degree of accuracy.

SCIDDICA ([13], [14], [15]) is a family of deterministic MCA models, specifically developed for simulating debris flows. These families of models have been developed according to an incremental strategy, permitted by the underlying CA features. Initially, the model considers only fixed basic characteristics of the phenomenon; real cases, whose evolution does not depend on other features, are selected for the validation purposes. This permits to consider the first model of the family for less complex cases; new versions are generated step by step by introducing other features which control the analysed phenomenon occurring in other real cases.

The first release  $T$  of SCIDDICA was a simple CA model with purely gravitational flows and was validated on the Tessina (Italy) earth flow [14] characterised by a velocity up to few meters per day. The subsequent release  $O$ , applied to the Mt. Ontake (Japan) debris avalanche, is a crucial extension of the basic  $T$  model [15]. The considered landslide was extremely rapid (20–26 m/s) and thus characterised by relevant run-up effects (briefly described in the following). The successive  $S_x$  releases of SCIDDICA were developed for simulating debris flows which were characterised also by strong soil erosion along the landslide path; they were validated on the Sarno debris flows (see [8], [13], [16], [17]) with various improvements concerning inertial effects. The last challenge concerned the releases  $SS_x$  of the SCIDDICA family, that is an extension to combined subaerial-subaqueous flow-type landslides, with a new flows characterization by their mass centre position and velocity [11]. The extremely accurate investigation of the 1997 Lake Albano (Italy) subaerial-subaqueous debris flow [18] permitted to validate the model and to compare this MCA simulator with others based on differential equations systems [19].

In the next Sections, the MCA general framework is presented, together with some MCA models for debris flow simulation of the SCIDDICA family. Afterwards, some results on case studies and conclusions are reported.

## 2 Macroscopic Cellular Automata

CA were introduced for the first time by the mathematician John von Neumann [1]. They are a parallel computation model whose evolution is governed by laws which are purely local. The dynamics of global complex systems simulated with CA “emerge” from the “local interactions” of their “elementary components”. The methodology adopted in CA models is generally empirical-inductive: starting from the observation of the phenomenon that one intends to model, trying to identify the essential mechanism and developing some hypothesis on the possibility to describe the overall behaviour on the basis of laws that determine the interaction mechanisms among the basic components. Subsequently, one defines a model that translates in formal terms the identified laws and adopting a verification phase prior to a monitoring one, necessary to evaluate the reliability of the model in relation to the real phenomenon. When modelling natural phenomena, CA can be intuitively considered as a three or two-dimensional space (the cellular space), partitioned into cells of uniform size. Each cell embeds an identical finite automaton ( $fa$ ), whose states identify the properties of the portion of space corresponding to the cell which are considered “significant” for the evolution of the phenomenon. The states of the  $fa$  in the neighbouring cells are given as input for each  $fa$ . At time  $t=0$ , each  $fa$  is in an “arbitrary” state; the model then evolves by changing, at discrete times and simultaneously, the state of all finite automata according to rules invariant in time, by applying the so-called “transition function” depending on the cell neighbourhood.

The MCA formalism introduces some extensions with respect to the classical definition of CA. Major novelties regard the state of a cell, which is decomposed in “substates”, each one representing a particular feature (e.g. lava temperature, debris amount, etc) of the phenomenon to be modelled. The state of the cell thus belongs to the Cartesian product of the considered substates. In addition, some “parameters” are generally considered, which allow to “tune” the model for reproducing different dynamical behaviours of the phenomenon of interest. Moreover, even the state transition function is split in “elementary processes”, each one describing a particular aspect of the considered phenomenon.

### 2.1 The Minimisation Algorithm of the Differences

Natural phenomena, which evolve by generating flows of some material at a macroscopic level of description, are particular suitable to be modelled through MCA. In fact, if the cell dimension is a constant value throughout the cellular space, as usually occurs in MCA models, it is possible to consider characteristics of the cell (i.e. substates), typically expressed in terms of volume (e.g. debris volume), in terms of thickness. This simple assumption permits to adopt a efficacious strategy that computes outflows from the central cell to the neighbouring ones in order to minimize the non-equilibrium conditions. Outflows computation is performed by applying an opportune (i.e. depending on the particular

phenomena to model) version of the “Minimization Algorithm of the Differences” [5]. The algorithm, in its general version, is explained briefly in section 3.3.

## 3 The SCIDDICA family models

In the past years, the MCA SCIDDICA family models have improved, exhibiting a better reproduction of the phenomenon characteristics to be simulated. This is also due to a continuous refinement of the adopted approach that has furthermore given rise to a more general modelling framework with the birth the SCIDDICA  $SS_x$  models type. As a matter of fact, after the first simulations referred to the landslide occurred on Mount Ontake (Japan), major attention was dedicated to morphological irregularities that can be present which can produce great turbulence effects and energy dissipation. As a consequence, the initial empirical strategy based on the Minimisation Algorithm has been enriched with a new elementary process for the *run-up* determination, which is determined by the thickness of the landslide debris plus a fictitious height, named *kinetic head* (see Section 3.2).

In the case of more regular morphological conditions (for instance, in a plane area or slight slope), energy dissipation results smaller and the direction of the momentum is less subject to abrupt variations (due to the lack of morphological obstacles). In such a case, the flow inertial effects can play a significant role in the dynamics of the system and the original Minimisation Algorithm, as propounded in the  $O$  version of the model, could not be adequate. To solve this problem, D’Ambrosio and co-workers have developed the  $S_x$  family models which introduce new characteristics ([16], [13], [20]). Initially, the release  $S_x$  of SCIDDICA was developed for simulating the 1998 Sarno (Campania, Southern Italy) debris flows, which were characterized by strong soil erosion along the landslide path. The release  $S_1$  was derived and tested on the Curti (Sarno, Italy) case study. By analysing the results of performed simulations and by quantitatively comparing the model outputs with the map of the landslide, further modifications affecting the energy balance were implemented, and the release  $S_2$  was obtained [20]. The need for simulating multiple landslides that contemporarily develop in the cellular space, besides the mechanism of progressive erosion of the regolith based on the energy of the moving mass, led to the release  $S_3$  [16]. Other improvements that incorporate a better management procedure for the inertial effects which characterize rapid debris flows were finally introduced in the transition function of the model, giving rise to the release  $S_4$  [17].

Together with this latest release of the  $S_x$  family models - and as an alternative to these - the  $SS_x$  family models were released in 2008 [11]. These latter were implemented with the need to simulate combined subareal-subaqueous landslides. In the  $SS_1$  version, the concept of run-up is still present, considered as the combination of the kinetic head plus debris. At the contrary, in the  $SS_2$  models, the run-up effect for fast moving landslides is expressed in a

different manner. Here, the kinetic head is not considered as a whole with the debris, but computed separately from it in order to explicitly consider the physical characteristics related to energy loss and landslide velocity. It is worth saying that  $SS_1$  is a passing version, which inherits a lot of the SCIDDICA  $S_3$  model, even if somewhat less accordant with the physical characteristics of the considered simulated phenomena, while many of these limits are surpassed by  $SS_2$ .

Table 1. SCIDDICA: list of considered substates

<b>Substate</b>	<b>Meaning</b>	<b>Model</b>
$Q_a$	Altitude (in meters)	$T, O, S_1, S_2, S_3, S_4, SS_2$
$Q_{th}$	Thickness of landslide debris (in meters)	$T, O, S_1, S_2, S_3, S_4, SS_2$
$Q_r$	Run-up height, depending on the kinetic energy of the landslide and expresses the height that can be overcome by the debris flow (in meters)	$O, S_1, S_2, S_3,$
$Q_d$	Maximum depth of detrital cover that can be transformed by erosion in landslide debris, it depends on the type of detrital cover (in meters)	$S_3, S_4, SS_2$
$Q_o$ ( $Q_i$ )	Debris outflow (inflow) (in meters)	$T, O, S_1, S_2, S_3, S_4, SS_2$
$Q_E$	Total Energy of landslide debris (in joule)	$S_4, SS_2$
$Q_{px}, Q_{py}$	Represent indicators (as velocity is not explicitly given at the level of a single cell in the CA context of the model SCIDDICA $S_4$ ) of the momentum of the landslide debris, along the directions $x$ and $y$ , respectively. They are named inertial substates and expressed in terms of momentum (in kg m/s)	$S_4$
$Q_x, Q_y$	Coordinates of the debris barycentre with reference to the cell centre (in meters)	$SS_2$
$Q_{th}$	Debris kinetic head (in meters)	$SS_2$
$Q_{oe}$ ( $Q_{oi}$ )	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)	$SS_2$
$Q_{XE}, Q_{YE}$ ( $Q_{XI}, Q_{YI}$ )	Coordinates of the external flow barycentre (internal flow barycentre) with reference to the adjacent cell centre (in meters)	$SS_2$

The release  $S_4$  and  $SS_2$  of the family SCIDDICA overcome a typical restriction of many CA models, including lattice Boltzmann 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). SCIDDICA  $SS_2$  introduces coordinates of mass centre of flows and

computes their shift. In this case, velocity is locally explicit: the mass centre of a flow can need several steps to cross a cell. The resulting new mass, barycentre and velocity are computed by the composition of all inflows from the neighbours and residual quantities inside the cell. This method was firstly applied to lava flows ([21], [22]), while the extension to debris flows involved more complex criteria to be considered. The SCIDDICA  $S_4$  model, instead, introduces explicitly conservation laws concerning momentum, even if velocity of flows quantities from the central cell to adjacent cells is ruled without explicit mass centre specifications; on the other side, SCIDDICA  $SS_2$  lacks of explicit momentum.

Table 2. SCIDDICA: list of considered parameters

<b>Parameter</b>	<b>Meaning</b>	<b>Model</b>
$p_c$	Side of the cell (in meters)	$T, O, S_1, S_2, S_3, S_4, SS_2$
$p_t$	Temporal correspondence of a step of SCIDDICA (in seconds)	$T, O, S_1, S_2, S_3, S_4, SS_2$
$p_{adh}^*$	Water/Air adherence value (i.e. unmovable amount of landslide debris) (in meters)	$T, O, S_1, S_2, S_3, S_4, SS_2$
$p_r$	Relaxation rate of debris landslide outflows (a delaying factor ranging between 0 and 1 by which the amount of debris to be distributed among the cells is multiplied at each step), which are multiplied by this parameter (dimensionless)	$O, S_1, S_2, S_3$
$p_{rl}$	Run-up loss at each step (owing to frictional dissipation) (in meters)	$O, S_1, S_2, S_3$
$p_f^*$	Water/Air height threshold (related to friction angle) for debris outflows. It expressed as the minimum difference of height between two cells for the debris distribution to be allowed (dimensionless)	$O, S_1, S_2, S_3, S_4, SS_2$
$p_{mi}^*$	Water/Air activation threshold of the mobilization (in meters)	$S_1, S_2, S_3, S_4, SS_2$
$p_{er}^*$	Water/Air parameter of progressive erosion of the soil cove (dimensionless)	$S_1, S_2, S_3, S_4, SS_2$
$p_{td}^*, p_{ed}^*$	Water/Air parameters for energy dissipation by turbulence and by erosion respectively (dimensionless)	$SS_2$
$p_{mi}$	Matter loss in percent when the debris enters into water (dimensionless)	$SS_2$
$p_{wr}$	Water resistance parameter (dimensionless)	$SS_2$

The latest MCA model (SCIDDICA- $SS_2$ ) involves new substates, local interactions, internal transformations and parameters but, most of all, represents a new method to simulate combined subaerial-subaqueous flow-like landslides. Positive experiments, in fact, were carried out on the Lake Albano (Central Italy) event, a complex landslide

to simulate, particularly for what concerns the water/air interface region.

### 3.1 The SCIDDICA family general characteristics

The main models' characteristics, which are common to all versions of the SCIDDICA family here presented, can be summarized by the following points:

- they are bi-dimensional models, based on hexagonal cells, but simulations are effectively three-dimensional, because the third dimension is included in the specification of the cell state;
- the cell neighbourhood,  $X$ , is composed by the cell itself and the six adjacent ones;
- debris flows are computed by applying the Minimisation Algorithm of the Differences.

In Table 1 and Table 2,  $T$ ,  $O$ ,  $S_x$  and  $SS_2$  specify substates and parameters which characterize the MCA models used in the Tessina, Mt. Ontake, Sarno and Albano cases of study, respectively. In Table 2, the “\*” symbol at the end of the parameter name is considered when the formula is valid both in water and air.

### 3.2 The SCIDDICA family in formal terms

In formal terms, and in its hexagonal version, a generic SCIDDICA family model can be seen as a quintuple:

$$\text{SCIDDICA} = \langle R, X, Q, P, \sigma \rangle$$

where

- $R = \{(x, y) \in Z^2 \mid -l_x \leq x \leq l_x, -l_y \leq y \leq l_y\}$ , identifies the hexagonal cellular space where the phenomenon evolves;  $Z$  is the set of integers.
- $X = \{(0, 0), (1, 0), (0, 1), (0, -1), (-1, 0), (-1, 1), (1, -1)\}$  is the geometrical pattern of the neighbourhood of the cell, given by the “central” cell and its six adjacent cells.
- $Q = Q_{x_1} \times Q_{x_2} \times \dots \times Q_{x_n}$  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, let  $q_x$  and  $\Delta q_x$  indicate the values of a substate  $Q_x$  and its variation, respectively. 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 (Table 2) which account for the general frame of the model and the physical characteristics of the phenomenon.
- $\sigma: Q^7 \rightarrow Q$  is the deterministic transition function for the cells in  $R$ .

At the beginning of the simulation ( $t = 0$ ), the states of the cells in  $R$  must be specified, defining the initial configuration of the MCA. Initial values of the substates (Table 2) are initialised as follows:

- $Q_a$  is set to the altitude (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;
- $Q_E$  (or  $Q_r$ ) 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;
- $Q_o, Q_i, Q_{px}, Q_{pv}, Q_v, Q_y, Q_{oe}, Q_{oi}, Q_{kh}$ , are set to 0 everywhere.

The transition function  $\sigma$  is applied, step by step, to all the cells in  $R$ , and the CA configuration changes obtaining the evolution of the simulation.

### 3.3 Elementary processes of the transition function

In this section we will show some salient SCIDDICA elementary processes. In the following,  $\sigma_T, \sigma_O, \sigma_{S_x}$  and  $\sigma_{SS_2}$  indicate the transition function of the models  $T, O, S_x$  and  $SS_2$ , respectively. Please refer to [13], [14], [15], [11] for a more in-depth knowledge of the considered models.

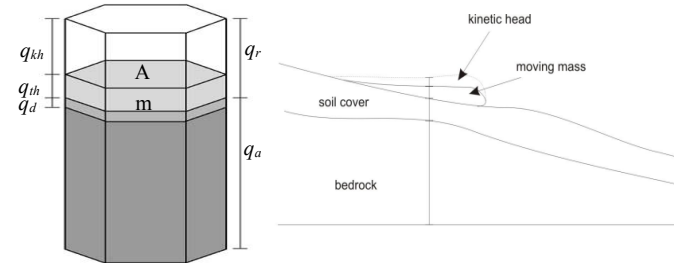


Figure 1: Left: relationship in a hexagonal cell between the values  $q_a, q_d, q_{th}$  and  $q_r$  of the substates  $Q_a, Q_d, Q_{th}$  and  $Q_r$ , respectively, and of the kinetic head  $q_{kh}$ . Right: an ideal vertical section of a debris flow along a slope is also given

**Basic assumptions.** An important requirement regards the energy definition which is used in some releases of SCIDDICA. Let us first consider a “column” of mass  $m$  (with constant density  $\rho$ ), with base  $A$  and thickness  $h = q_{th}$  at altitude  $z = q_a$  (with respect to the plane  $z = 0$ ) (Figure 1), which moves at velocity  $v$ . If  $E_u$  and  $E_k$  represent the potential and the kinetic energy, respectively, the total energy of the column,  $E$ , is given by the following expression:

$$E = E_u + E_k = \rho g A \int_z^{z+h} z dz + \frac{1}{2} \rho A h v^2$$

where  $g$  is gravity acceleration. In hydrodynamics [23], the kinetic head,  $h_k$ , is defined as:  $h_k = v^2/2g$ . Thus:

$$E = \rho g A h \left( \frac{1}{2} h + z + h_k \right) \quad (1)$$

while

$$E_k = \rho g A h h_k \Rightarrow h_k = \frac{E_k}{\rho g A h} \quad (2)$$

Some debris flows can be very rapid, implying a run-up,  $r$ , which depends on the velocity associated to debris; therefore  $r = h_k + h$  which implies  $r = v^2/2g + h$ .

**Run-up computation in  $\sigma_0$ ,  $\sigma_{S1}$ ,  $\sigma_{S2}$ ,  $\sigma_{S3}$ .** The run-up  $q_r$  is computed as the weighted average of the total heights related to the residual debris thickness and to the neighbourhood inflows, minus the altitude of the central cell ( $q_a$ ) and the run-up losses due to friction ( $p_{rl}$ ). The effect of energy loss owing to frictional dissipation is modeled at each step. The new value of run-up is obtained as follows:  $new\_q_r = q_r - p_{rl}$ .

In this release, losses of energy (in terms of run-up times debris thickness) and inertia (which is a function of the run-up) are implicitly induced.

**Regolith Erosion in  $\sigma_{S3}$ ,  $\sigma_{S4}$ ,  $\sigma_{SS2}$ .** Aiming at accounting for the occurrence of partial erosion of the regolith along the path, the following empirical strategy has been developed based on the parameters  $p_{mt}$  and  $p_{er}$ . In terms of altitude variation, it is given by the following expression:

$$\begin{aligned} \text{In } SS: \quad \Delta q_a &= \begin{cases} 0 & \text{if } q_{kh} \leq p_{mt} \vee q_{kh} = 0 \\ \min(q_d; (q_{kh} - p_{mt}) \times p_{er}) & \text{if } q_{kh} > p_{mt} \end{cases} \\ \text{In } S_3/S_4: \quad \Delta q_a &= \begin{cases} 0 & \text{if } q_E \leq p_{mt} \vee q_{kh} = 0 \\ \min(q_d; q_E \times p_{er}) & \text{if } q_E > p_{mt} \wedge q_{kh} > 0 \end{cases} \end{aligned}$$

Consequently, the new values of altitude, regolith and landslide debris, due to erosion, are updated as follows:

$new\_q_a = q_a - \Delta q_a$ ;  $new\_q_d = q_d - \Delta q_a$ ;  $new\_q_{th} = q_{th} - \Delta q_a$   
 In particular, in the release  $SS_2$ , the new value of total energy,  $new\_q_E$ , is recomputed with respect to the new altitude of the cell,  $new\_q_a$ , (Equation 1); moreover, the mixing of the eroded detrital cover with the previous debris involves that the previous debris kinetic energy becomes equal to the kinetic energy of all the debris mass, implicating trivially a further kinetic head reduction (i.e. energy dissipation by erosion):

$$\Delta q_{kh} = p_{ed} \times \Delta q_a; \quad new\_q_{kh} = q_{kh} - \Delta q_{kh}$$

**Computation of minimising debris outflows in  $\sigma_T$ ,  $\sigma_0$ ,  $\sigma_{S1}$ ,  $\sigma_{S2}$ ,  $\sigma_{S3}$ ,  $\sigma_{S4}$ ,  $\sigma_{SS2}$ .** Outflows from the central cell towards the neighbouring ones are computed by applying the ‘‘Minimisation Algorithm of the Differences’’ [5], [21]. The algorithm is based on the following assumptions:

- In the central cell, an unmovable amount,  $u(0)$ , and another one which can be distributed to the neighbours,  $m$ , are generally found. Here,  $m = \sum_{i=0}^6 q_o(i)$  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,  $u(i)$  ( $i = 1, 2, \dots, 6$ ), is considered unmovable.

The following is valid for all SCIDDICA models:

$$\begin{aligned} m &= q_{th}(0) - p_{adh}; \\ u(0) &= q_a(0) + p_{adh} + w(0); \\ u(i) &= q_a(i) + q_{th}(i) + w(i); \end{aligned}$$

where  $w$  depends from the model version (e.g. for the  $SS_2$  release  $w(0)=q_{kh}$ ;  $w(i)=0$ ). More precisely, the algorithm minimises the following expression [21]:

$$\sum_{(i,j)/0 \leq i < j \leq 6} (u(i) + q_o(i)) - (u(j) + q_o(j))$$

In general:  $new\_q_{th} = q_{th} + \sum q_i - \sum q_o$ . Note that a preliminary test is performed before applying the Minimisation Algorithm, in order to account for frictional effects: these latter effects may inhibit debris outflows, in case the difference in height between two cells is smaller than  $p_f$ , i.e. if  $u(0) + m - u(i) < p_f$ .

**Computation of momentum in  $\sigma_{S4}$ .** Indicators of momentum ( $q_{px}$ ,  $q_{py}$ ), concerning the inflows into the central cell, are computed as follows:

$h_i = h[i] - h[0] = (q_a[i] + q_r[i]) - (q_a[0] + q_{th}[0] + q_r[i,0])$  ( $i=1, 2, \dots, 6$ ) is the height difference between the  $i$ -th neighbouring cell and the central cell, being  $q_r[i,0]$  the amount of run-up related to the debris which moves from the  $i$ -th neighbouring cell into the central cell;  $v_i = \sqrt{2gh_i}$  is the velocity of the debris coming from the  $i$ -th neighbouring cell into the central cell;  $\mu[i] = v_i q_r[i,0]$  is the  $i$ -th component of the momentum indicator for the central cell. The vectorial composition of these indicators returns the new values of the substates  $q_{px}$ ,  $q_{py}$ .

**Shift of the Outflows in  $\sigma_{SS2}$ .** Outflows computation is performed in two steps: determination of the outflows minimising the ‘‘height’’ differences in the neighbourhood ([5], [21], [22]) and determination of the shift of the outflows. The  $SS_2$  version introduces a novelty with respect to former versions, where the shift of the outflows is computing according to the simple kinetic formula which depends whether the flow is subaerial or subaqueous. In fact, the shift formula for subaqueous debris considers also the water resistance, using modified Stokes equations with a form factor that is proportional to mass:  $p_{wr}$ . The motion involves three possibilities: (1) only internal flow ( $q_{oe}=0, q_{oi} \neq 0$ ); (2) only external flow ( $q_{oe} \neq 0, q_{oi}=0$ ); (3) the flow is divided between the central and the adjacent cell ( $q_{oe} \neq 0, q_{oi} \neq 0$ ). When debris outflows are computed, the new value of  $q_{th}$  is given:  $new\_q_{th} = q_{th} + \sum q_i - \sum q_{oe}$ .

The co-ordinates determination of barycentre is calculated as the average weight of  $q_x$  and  $q_y$ , considering the remaining debris in the central cell, the internal flows and the inflows.

**Turbulence Effect ( $\sigma_{SS2}$ ).** A total energy reduction in a cell is considered by loss of flows, while an increase is given by inflows; moreover, the new value of the kinetic head is deduced from the computed kinetic energy (Equation 2) and energy dissipation  $p_{td}$ , computed over the kinetic head, was considered as a turbulence effect.

**Air-Water Interface ( $\sigma_{SS2}$ ).** 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 proportional to debris mass, specified by  $p_{ml}$ .

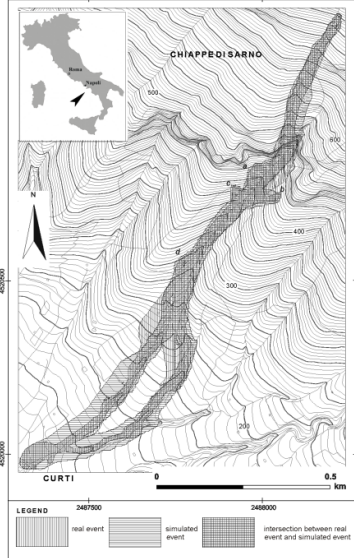


Figure 2: The 1998 Sarno debris flow as simulated by the SCIDDICA  $S_4$  model. Key: (1) real event, (2) simulated event, (3) intersection between real and simulated event.

### 3.4 SCIDDICA applications

In this section, examples of application of the previous release of the model SCIDDICA  $S_4$  to the case studies of Sarno (Italy) and an example of application of the new release SCIDDICA  $SS_2$  to the Albano lake (Italy) case are briefly presented. Recently,  $SS_2$  has been used to simulate a completely submarine landslide occurred near the town of Bagnara (South Italy) in November 2007 [24]. For more details on the real landslide cases and on the simulations, please refer to the specific references given previously in the text.

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 cases of Sarno and Albano such value is considered as 0.7.

**The Sarno event.** On May 5<sup>th</sup> 1998, about 150 debris flows were triggered by exceptional rainfalls in the Sarno area (Campania, Southern Italy), mostly on the slopes of the Pizzo d’Alvano massif [13]. Hundreds of small debris slides originated in the volcanoclastic mantle, on the uppermost portions of the slopes, and rapidly transformed into fast-moving debris flows. In Figure 2 an example of the Sarno landslide simulation as performed by the  $S_4$  SCIDDICA model is shown, where a good fitness value of 0.77 was obtained.

**The Lake Albano event.** The SCIDDICA  $SS_2$  model was validated against the 1997 Albano lake (Rome, Italy) event (Figure 3) which is a rare case of combined subaerial-subaqueous debris-flow [18]. This landslide occurred in the eastern slope of the Albano Lake on November 7<sup>th</sup> 1997, after an intense rainfall event. Simulations permitted to validate the general model and to calibrate adequately its parameters; results show a good agreement concerning erosion and deposits on both subaerial and subaqueous part and reasonable values of the landslide velocity (up to 15 m/s). First model results were encouraging: the value 0.85 was obtained for the fitness function  $e_1$  and has confirmed a satisfying reliability of this preliminary model in reproducing the phenomenon.

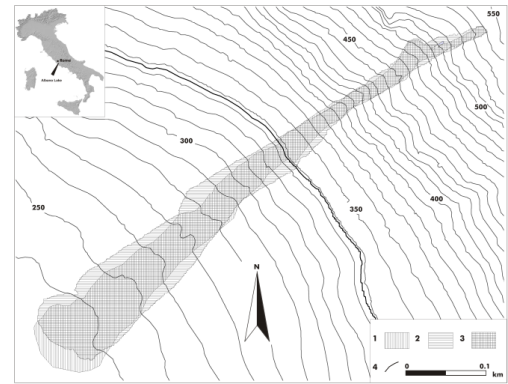


Figure 3: The 1997 Albano lake subaerial-subaqueous debris flow as simulated by the SCIDDICA  $SS_2$  model. Key: (1) real event, (2) simulated event, (3) intersection between real and simulated event, (4) water level.

## 4 Conclusions

We have presented a brief overview of a methodological framework which can be adopted for simulating complex natural phenomena. The methodology can be considered effective when the modeling of such phenomena can be very difficult to be managed with differential equation systems. Specifically, this paper shows how MCA can be applied to flow-type landslides simulations within the context of the SCIDDICA family models, with particular reference to the hexagonal release for the simulation of flow-type landslides. The last release ( $SS_2$ ) is the most advanced model of the SCIDDICA family and could be usefully used in hazard analyses for subaerial, subaqueous and combined flow-type landslides; applications to other cases are also planned.

Eventually, a first version of a CA model for the simulations of dense snow avalanches based on SCIDDICA-SS<sub>2</sub> is being developed.

## 5 References

- [1] John von Neumann. "Theory of Self Reproducing Automata". University of Illinois Press, Urbana, 1966.
- [2] U. Frisch, B. Hasslacher, Y. Pomeau. "Lattice-gas Automata for Navier Stokes Equation"; *Physical Review Letters* 56 (14), 1505-1508, 1986.
- [3] S. Succi, R. Benzi, F. Higuera. "The lattice Boltzmann equation: a new tool for computational fluid dynamics"; *Physica* 47 (D), 219-230, 1991.
- [4] D.L. Stein. "Lectures in the Sciences of Complexity", Addison Wesley, Redwood City, CA, USA, 1989.
- [5] S. Di Gregorio, R. Serra. "An empirical method for modelling and simulating some complex macroscopic phenomena by cellular automata"; *Future Generation Computer Systems*, Vol. 16, 259–271, 1999.
- [6] G.M. Crisci, S. Di Gregorio, G.A. Ranieri. "A cellular space model of basaltic lava flow"; *Proceedings AMSE Conference Modelling & Simulation*, (Paris, France, Jul.1-3), 65–67, 1982.
- [7] G.M. Crisci, R. Rongo, S. Di Gregorio, W. Spataro. "The simulation model SCIARA: the 1991 and 2001 lava flows at Mount Etna"; *Journal of Volcanology and Geothermal Research*, Vol. 132, 253–267, 2004.
- [8] G. Iovine, D. D'Ambrosio, S. Di Gregorio. "Applying genetic algorithms for calibrating a hexagonal cellular automata model for the simulation of debris flows characterised by strong inertial effects"; *Geomorphology*, 287-303, 2005.
- [9] M.V. Avolio, G.M. Crisci, S. Di Gregorio, R. Rongo, W. Spataro, D. D'Ambrosio. "Pyroclastic flows modelling using cellular automata"; *Computers and Geosciences-UK*, Vol. 32, 897–911, 2006.
- [10] S. Di Gregorio, D.C. Festa, R. Rongo, W. Spataro, G. Spezzano, D. Talia. "A microscopic freeway traffic simulator on a highly parallel system"; *Parallel Computing: State-of-the-Art and Perspectives*, E.H. D'Hollander, G.R. Joubert, F.J. Peters and D. Trystam (Eds.), 69–76, 1983.
- [11] M.V. Avolio, V. Lupiano, P. Mazzanti, S. Di Gregorio. "Modelling combined subaerial-subaqueous flow-like landslides by Cellular Automata"; *Proceedings of ACRI 2008*, Sept 23-26, Japan, LNCS 5191, 329-336, 2008.
- [12] M.V., Avolio, G.M. Crisci, D. D'Ambrosio, S. Di Gregorio, G. Iovine, R. Rongo, W. Spataro. "An extended notion of Cellular Automata for surface flows modelling"; *WSEAS Transactions on Computers*, 4 (2), 1080-1085, 2003.
- [13] D. D'Ambrosio, S. Di Gregorio, G. Iovine, V. Lupiano, R. Rongo, W. Spataro. "First simulations of the Sarno debris flows through Cellular Automata modeling"; *Geomorphology* 54, 91-117, 2003.
- [14] M.V. Avolio, S. Di Gregorio, F. Mantovani, A. Pasuto, R. Rongo, S. Silvano, W. Spataro. "Simulation of the 1992 Tessina landslide by a Cellular Automata model and future hazard scenarios"; *JAG e Journal of Applied Earth Observation and Geoinformation* 2 (1), 41-50, 2000.
- [15] S. Di Gregorio, R. Rongo, C. Siciliano, M. Sorriso-Valvo, W. Spataro. "Mount Ontake landslide simulation by the cellular automata model SCIDDICA-3"; *Physics and Chemistry of the Earth* 24 (A), 97-100, 1999.
- [16] D. D'Ambrosio, S. Di Gregorio, G. Iovine. "Simulating debris flows through a hexagonal Cellular Automata model: Sciddica S3-hex"; *Natural Hazards and Earth System Sciences* 3, 545-559, 2003.
- [17] D. D'Ambrosio, G. Iovine, W. Spataro, H. Miyamoto. "A macroscopic collisional model for debris-flows simulation"; *Environmental Modelling and Software*, Volume 22, 10, 1417-1436, 2007.
- [18] P. Mazzanti, F. Bozzano, C. Esposito. "Submerged Landslides Morphologies in the Albano Lake (Rome, Italy)"; *Proceedings of 3rd Intern. Symp. "Submarine Mass Movements and Their Consequences"*, 27, 243-250. Springer, Heidelberg, 2007.
- [19] P. Mazzanti, F. Bozzano, M.V. Avolio, V. Lupiano, S. Di Gregorio. "3D numerical modelling of submerged and coastal landslides propagation"; In: Mosher, D.C., Shipp, C., Moscardelli, L., Chaytor, J., Baxter, C., Lee, H. and Urgeles, R. (eds). *Submarine Mass Movements and Their Consequences IV; Advances in Natural and Technological Hazards Research*, Vol 28, DOI 10.1007/978-90-481-3071-9, Springer, The Netherlands, 127-139, 2009.
- [20] D. D'Ambrosio, S. Di Gregorio, G. Iovine, V. Lupiano, L. Merenda, R. Rongo, W. Spataro. "Simulating the Curti-Sarno Debris Flow through Cellular Automata: the model SCIDDICA (release S2)"; *Physics and Chemistry of the Earth*, 27, 1577–1585, 2002.
- [21] M.V. Avolio. "Esplicitazione della velocità per la modellizzazione e simulazione di flussi di superficie macroscopici con automi cellulari ed applicazioni alle colate di lava di tipo etneo". Ph. D. Thesis (in Italian). Dept. of Mathematics, University of Calabria, 2004.
- [22] M.V. Avolio, G.M. Crisci, S. Di Gregorio, R. Rongo, W. Spataro, G.A. Trunfio. "SCIARA  $\gamma$ 2: an improved Cellular Automata model for Lava Flows and Applications to the 2002 Etnean crisis"; *Computers & Geosciences*, 32, 897-911, 2006.
- [23] E. Marchi, A. Rubatta. "Meccanica dei fluidi". Principi e applicazioni. UTET, Torino, 1981(120) H. Rouse. *Engineering Hydraulics*. John Wiley & Sons, Chichester, 1950.
- [24] Avolio, M.V., Lupiano, V., Mazzanti, P., Di Gregorio, S.: A Cellular Automata Model for Flow-like Landslides with Numerical Simulations of Subaerial and Subaqueous Cases. In Wohlgenuth, V., Page, B., Voigt, K. (eds), *EnviroInfo 2009*, Vol. 1, pp. 131--140, Shaker Verlag GmbH, Aachen (2009)