Simulations of Debris/Mud Flows Invading Urban Areas: A Cellular Automata Approach with SCIDDICA

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Abstract. Different methodologies are used for modelling flow-like landslides. A critical point concerns the flooding of town areas, which cannot be assimilated straight to a morphology, especially, when the urban tissue is very irregular with narrow streets and setting of buildings, which reflect historical contingencies. SCIDDICA is a competitive (related to PDE approach) Cellular Automata model for 3-dimensions simulation of flow-like landslides. This paper presents innovations to the transition function of SCIDDICA-SS2, which manage opportunely building data in the cells corresponding to the urban tissue. That permits to simulate the complete evolution of landslides, from the detachment area to its exhaustion almost on the same precision level. This is an advantage for hazard and risk analyses in threatened zones. Improved SCIDDICA-SS2 was applied successfully to the well-known 2009 debris flows of Giampilieri Superiore also in comparison with simulation results of the previous versions.

Keywords: Cellular Automata · Modelling and Simulation · Debris flow · Natural hazard · SCIDDICA · Giampilieri Superiore

1 Introduction

Flow-like landslides of different types: debris flows, mudflows, lahars, rock avalanches are extremely dangerous surface flows, which can generate destructions with casualties in inhabited areas, especially in urban zones. Modelling and simulations of such natural disasters could be an important tool for hazard and risk mitigation and management in threatened regions.

Such complex fluid-dynamical phenomena are modelled through different standard approaches: empirical models, based on smart correlations of phenomenon observables, simple rheological and hydrological models, which assume acceptable

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simplifications, numerical methods approximating PDE [1, 2]. These various approaches can produce discordant results [3], because different objectives of the simulations could involve different levels of precision for different types of data. Simulation results have to be accurately interpreted according to the model features. Simulations produce usually a large amount of data, whose usage in validation stage is devoted to a comparison with real event data that are almost approximate in the evolution phase, but usually detailed for the final effects that represent secure comparison terms.

Cellular Automata (CA) represent an alternative numerical method for modelling dynamical complex systems, which evolve on the basis of local interactions of their constituent elements. A Cellular Automaton evolves in a discrete space-time. Space is partitioned in cells of uniform size, each cell embeds a finite states automaton (a computing unit), all the cells change simultaneously state according a transition function of the states of the neighbor cells, where the neighborhood conditions are determined by a pattern invariant in time and space [4]. An extension of classical CA, MCA, Multicomponent (alias Macroscopic) CA, was developed in order to model large scale (extended for kilometers) phenomena [4, 5]. MCA need a large amount of states, in order to describe "macroscopic" properties of the space portion corresponding to the cell; such states may be formally represented by means of sub-states (e.g., sub-state altitude, i.e., the average value of altitude in the cell), which specify the characteristics to be attributed to the state of the cell. This involves several advantages in the case of surface flows; quantities concerning the third dimension, i.e. the height, may be easily included among the MCA sub-states, e.g., the thickness of debris in the cell, permitting models in two dimensions, working effectively in three dimensions; limits of discreteness may be partially overcome, permitting valid refinements; e.g. debris in a cell can be expressed as a thickness, but a further specification could be introduced by specifying the sub-states "center mass co-ordinates".

Two MCA models were developed for flow-like landslide, SCIDDICA (several versions since 1987, e.g. [6–12]) for subaerial/subaqueous debris/mud/gra-nular flows and LLUNPIY for primary and secondary lahars [13–15].

A critical point of these models concerns the flooding of town areas; previous solutions assimilated the urban tissue to a morphology and provided for a cell dimension enough small to permit that the cell corresponds nearly entirely to a piece of the road-bed (altitude of the road-bed) or to a piece of building (altitude of the building).

When part of the urban tissue consists of narrow streets and very irregular setting of buildings, due to historical contingencies, such a solution could involve an extremely large amount of cells, if the complete evolution of landslides from the detachment area to its exhaustion has to be simulated. That could implicate unsustainable computing time with the number of cells multiplied at least some hundreds times, if we consider that the model validation and following hazard analyses can imply thousands of simulations [16].

An extension of SCIDDICA-SS2 [7, 8, 11] was developed and applied in order to overcome these problems. A new sub-state that encodes building data, is introduced and AMD (the algorithm of minimization of differences [5], first step for determining cell outflows) was expanded in order to account for different heights (part of the road-bed, parts of buildings) inside the same cell. Simulation results of the well-known catastrophic landslide that overran Giampilieri Superiore in 2009 are excellent.

A short presentation of SCIDDICA-SS2 with a detailed specification of extended AMD is in the next section, the third section reports and compares different simulations of Giampilieri debris flows, conclusions and comments appear at the end.

2 SCIDDICA-SS2 Extension to Urban Areas

SCIDDICA-SS2 [7, 8, 11], SCIDDICA-SS3 [9, 10, 12] and LLUNPIY [13–15] are our front-rank models for simulations of flow-like landslides. The extension of SCIDDICA-SS2 to urban areas and applied to Giampilieri events, could be introduced easily in SCIDDICA-SS3 that represents a more precise version, but involving long running times, or in LLUNPIY, an adaptation of SCIDDICA-SS3 to lahar features. The following description of SCIDDICA-SS2 considers only the part of subaerial flows, without lacking of generality; a successive section presents the extended AMD.

2.1 Main Specifications of SCIDDICA-SS2

The hexagonal CA model SCIDDICA-SS2 is the quintuple: $< R, X, S, P, \tau >$ where:

- $R = \{(x, y) | \, x, y \in \mathbb{N}, 0 \leq x \leq l_x, 0 \leq y \leq l_y\}$ is the set of points with integer co-ordinates, which individuate the regular hexagonal cells, covering the finite region, where the phenomenon evolves. $\mathbb{N}$ is the set of natural numbers.
- $X = \{(0, 0), (1, 0), (0, 1), (-1, 1), (-1, 0), (0, -1), (-1, -1)\}$, the neighborhood index, identifies the geometrical pattern of cells, which influence state change of the central cell: the central cell (index 0) itself and the six adjacent cells (indexes 1,..,6).
- S is the finite set of states of the finite automaton, embedded in the cell; it is equal to the Cartesian product of the sets of the considered sub-states (Table 1). The new sub-state C specifies the type of cell: normal cell; detachment cell, where the landslide originates (the detachment depth is encoded in the C value); urban cell, whose C value encodes the parts of cell at different altitudes together with the differences in altitude from the road-bed.

Table 1. Sub-states

Sub-states	Description
C, A, D	Type of **C**ell, cell **A**ltitude, erodible soil **D**epth
T, X, Y, K	Debris **T**hickness, co-ordinates ***X*** and ***Y*** of the debris barycenter inside the cell, **K**inetic Head
E_T, E_X, E_Y, E_K (6 components)	**E**xternal debris flow normalized to a Thickness, **E**xternal flow co-ordinates ***X*** and ***Y***, **K**inetic Head of **E**xternal flow
$I_T, I_X. I_Y, I_K$ (6 components)	**I**nternal debris flow normalized to a **T**hickness, **I**nternal flow co-ordinates ***X*** and ***Y***, **K**inetic Head of **I**nternal flow

- P is the set of the global physical and empirical parameters (Table 2), which account for the general frame of the model and the physical characteristics of the phenomenon, 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., turbulence dissipation, even if an acceptable value is fixed by the simulation quality by attempts, triggered by comparison of discrepancies between real event knowledge and simulation results.

Table 2. Physical and empirical parameters (with their physical dimensions)

Parameters	Description
a, t	cell **a**pothem (m), **t**emporal correspondence to a CA step (s)
$\boldsymbol{p_f}$	**f**riction coefficient **p**arameter (°)
$\boldsymbol{d_t, d_e, p_e, t_m}$	energy **d**issipation by **t**urbulence (-) and **e**rosion (-); parameter of **p**rogressive **e**rosion (-); **m**obilization **t**hreshold (m)

- τ: $S^7 \rightarrow S$ is the cell deterministic state transition, it accounts for the components of the phenomenon, the "elementary processes" that are sketched in the next section.

2.2 Outline of SCIDDICA-SS2 Transition Function

A MCA step involves the ordered application of the following elementary processes, which constitute the transition function; every elementary process implies the state updating. In the formulae, neighborhood index for sub-states and related variables is specified by subscript, if it is not referred to central cell; ΔQ means Q value variation, multiplication is explicitly "·".

Debris Outflows. Outflows computation is performed in two steps: determination of the outflows f_i towards the neighbor i, $1 \leq i \leq 6$, by the new AMD (described in Sect. 2.3) according to "heights" of the cell neighborhood and determination of the shift of the outflows [5, 7, 8].

The outflow could be represented as an ideal cylinder, tangent the next edge of the central hexagonal cell, whose barycenter corresponds to the debris barycenter inside the central cell, in direction to the center of the neighbor cell. The part of the outflow, which overcomes the central cell, constitutes the external flow, specified by external flow sub-states, while the remaining part, the internal flow, is specified by internal flow sub-states. Shift "Δs" is computed according to the following simple formula, which averages the movement of all the mass as the barycenter movement of a body on a constant slope θ with a constant friction coefficient: $\Delta s = v \cdot t + g \cdot (\sin\theta - p_f \cos\theta) \cdot t^2/2$ with "g" gravity acceleration and initial velocity $v = \sqrt{(}2 \cdot g \cdot K)$ [7, 8].

Turbulence Effect. A turbulence effect is modelled by a proportional kinetic head loss at each SCIDDICA step: $-\Delta K = d_t \cdot K$. This formula involves that a velocity limit is asymptotically imposed de facto, for a maximum slope value.

Soil Erosion. When the kinetic head value overcomes an opportune threshold ($K > t_m$), depending on the soil features, then a mobilization of the detrital cover occurs proportionally to the quantity overcoming the threshold: $p_e \cdot (K - t_m) = \Delta T = -\Delta D$ (the erodible soil depth diminishes as the debris thickness increases), the kinetic head loss is: $-\Delta K = d_e \cdot (K - t_m)$.

Flows Composition. When outflows and their shifts are computed, the new situation involves that external flows leave the cell, internal flows remain in the cell with different co-ordinates and inflows (trivially derived by the values of external flows of the neighbor cells) have to be added. The new value of T is given, considering the balance of inflows and outflows with the remaining debris mass in the cell. A kinetic energy reduction is considered by loss of flows, while an increase is given by inflows: the new value of the kinetic head is deduced from the computed kinetic energy. X and Y are calculated as the average weight of the co-ordinates considering the remaining thickness in the central cell, the thickness of internal flows and the inflows.

2.3 AMD Adaptation for not Homogeneous Cells in SCIDDICA-SS2

The lack of homogeneity regards different altitudes for parts of the same cell. It involves a distinction of different rates of the cell area (normalized to unit), to which different altitudes and debris thicknesses correspond.

The following specification of AMD holds for SCIDDICA-SS2 with cells divided in two parts “R” (road-bed) and “B” (Building) with two areas of different altitude Preliminary definitions are given in the Table 3.

Table 3. Definitions for AMD adapted to urban areas

a_i	area rate related to the “R” part of the neighbor cell i, $0 \le i \le 6$
A_i	area rate related to the “B” part of the neighbor cell i, $0 \le i \le 6$
d	distributable quantity (as height) in the central cell
h_i	height of the “R” part of the neighbor cell i, $0 \le i \le 6$
H_i	height of the “B” part of cell i, $0 \le i \le 6$
f_i	flow toward the “R” part of the neighbor cell i, $0 \le i \le 6$
F_i	flow toward the “B” part of the neighbor cell i, $0 \le i \le 6$
h_i', H_i'	$h_i' = h_i + f_i$, $H_i' = H_i + F_i$, $0 \le i \le 6$

The values of the heights for the central cell is obtained by the sum of altitude and kinetic head for both the parts; the values of the heights for the adjacent cells is obtained by the sum of altitude and debris thickness for both the parts.

The adapted AMD (Table 4) finds f_i and F_i, $0 \le i \le 6$ that minimize:

$$\sum\nolimits_{\{(i,j)|0 \le i \le j \le 6\}} \left(\left| h_i' - h_j' \right| + \left| H_i' - H_j' \right| + \left| h_i' - H_j' \right| \right)$$

Table 4. AMD adapted to urban areas

Initialization:	a	both the "R" and "B" parts of all the neighbors are "admissible" to receive flows; R and B are the sets of admissible cell parts
Cycle:	b	$q = (d + \Sigma_{i\in R}\ (h_i \cdot a_i) + \Sigma_{i\in B}\ (H_i \cdot A_i))/(\Sigma_{i\in R}\ (a_i) + \Sigma_{i\in B}\ (A_i))$ is the "average height" for the set R *and* B of admissible cell parts.
	c	$h_x \geq q$, $(H_X \geq q)$ implies x (X) eliminated from R (B).
End of cycle:	d	go to step < b > until no cell is eliminated
Results:	e	$f_i = (q - h_i)\ a_i$ for $i\in \boldsymbol{R}$; $f_i = 0$ *for* $i\notin R$. $F_i = (q - H_i)\ A_i$ for $i\in \boldsymbol{B}$; $F_i = 0$ *for* $i\notin B$

3 Giampilieri Superiore Debris Flow Simulations

3.1 1st October 2009 Landslides Event

On the October 1st 2009 a severe meteorological event stroke the Peloritani Mountains (NE Sicily). The intense rainfall caused floods and triggered many debris and mud flows that brought 37 fatalities, numerous injured, several damages to public and private buildings, railways, roads, infrastructures, electric and telephonic networks, thousands of evacuated persons. The Department of Civil Protection of Sicilian Region has mapped more than 600 landslides, in an area, which stretched approximately for 50 km^2. Analysis of the rainfall event indicates a cumulative rainfall depth of 225 mm obtained in 9 h from the data recorded at the S. Stefano di Briga rain-gauge, with a peak of rainfall intensity of about 22 mm/min. The area is susceptible to the formation of debris flows due to lithological characteristics, complex tectonic history, high gradient of slopes (30–60°) and landscapes characterized by narrow gullies with hydraulic torrential regime.

Giampilieri Superiore was one of the most wounded villages by these catastrophic events. The village is located on the eastern slopes of the Peloritani Mountains on left side of Giampilieri River. In particular, it rises on an alluvial fan and is crossed by various creeks, tributaries of the Giampilieri River. All of them are characterized by small catchments with extension ranging from 0.03 km^2 to 0.1 km^2 [17]. The path of Sopra Urno creek, inside the urbanized area, was turned into a road (Chiesa Street, Fig. 1b). During the paroxysmal pluvial event of 1st October, several debris flows (Fig. 1a) were mobilized from the slope behind the village. Many of these channeled before in the drainage network and after in the Chiesa Street, reached Giampilieri Superiore, producing dramatic effects in terms of loss of human lives and damages of buildings.

The severity of the rainfall event was not the only cause of the disaster. In fact, other factors contributed to slope failures in the Giampilieri case, as Ardizzone et al. [18] stressed: abandoned terraced slopes lacking proper drainage and unmaintained dry walls; furthermore some village streets cover part of creek beds.

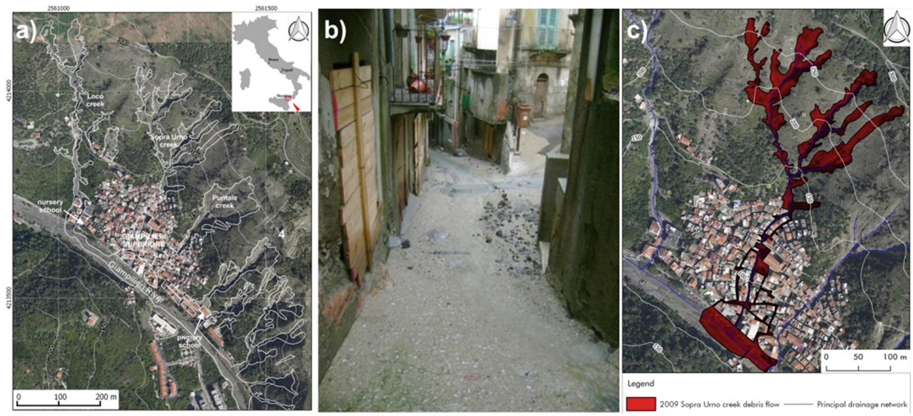

Fig. 1. (a) October 2009 debris flows occurred in Giampilieri Superiore, obtained by interpretation of aerial photo; (b) Example of Chiesa Street that during a normal rainfall event becomes the bed of the Sopra Urno creek; (c) Sopra Urno creek debris flow

3.2 Application of SCIDDICA SS2 to Sopra Urno Debris Flow

For testing the innovation introduced in SCIDDICA-SS2, we considered the Sopra Urno debris flow (mapped in Fig. 1c). SCIDDICA-SS2 and SCIDDICA–SS3 were calibrated and validated [10, 12, 15] on all debris flows occurred in Giampilieri Superiore area. The same parameters were used for simulations of this extended model. Genetic Algorithms were used for some key parameters related to energy dissipation in the previous versions of SCIDDICA; an analogous applications of Genetic Algorithm could improve the simulation quality.

Sopra Urno debris flow caused the largest number of casualties and damages, due to the fact that the flow crossed the village. Three experiments have been performed: the first one on a DTM (Digital Terrain Model), the second and third one on a DEM (Digital Elevation Model). The terms DTM and DEM are often confused. The principal difference between the two digital models lies in the fact that the DEM takes into account all objects on the ground (vegetation, buildings and other artifacts), while the DTM shows the geodesic surface. The difference between the two models is more evident in urban areas where buildings prevail.

First experiment, shown in Fig. 2a and a′, simulates the event, by considering the elevation at ground level in the urbanized area. The flows at the change of slope, reduce the speed, and give rise to the typical fan shape of debris.

A second test (Fig. 2b and b′) was performed using a DEM, which was obtained from manipulation of DTM by inserting urban data related to buildings and roads and by approximating altitude to road-bed. The flows, when reached the urbanized area, insinuates among the buildings. The results show a good capability of the model to simulate the debris run-out, particularly, in the upslope parts of the basins, while in the downslope urbanized area, the reproduction of the real events is less accurate. In fact, significant differences do exist in the lateral spreading characteristics of the run-out, as the streets inundated by the debris in the real event are different from those resulting

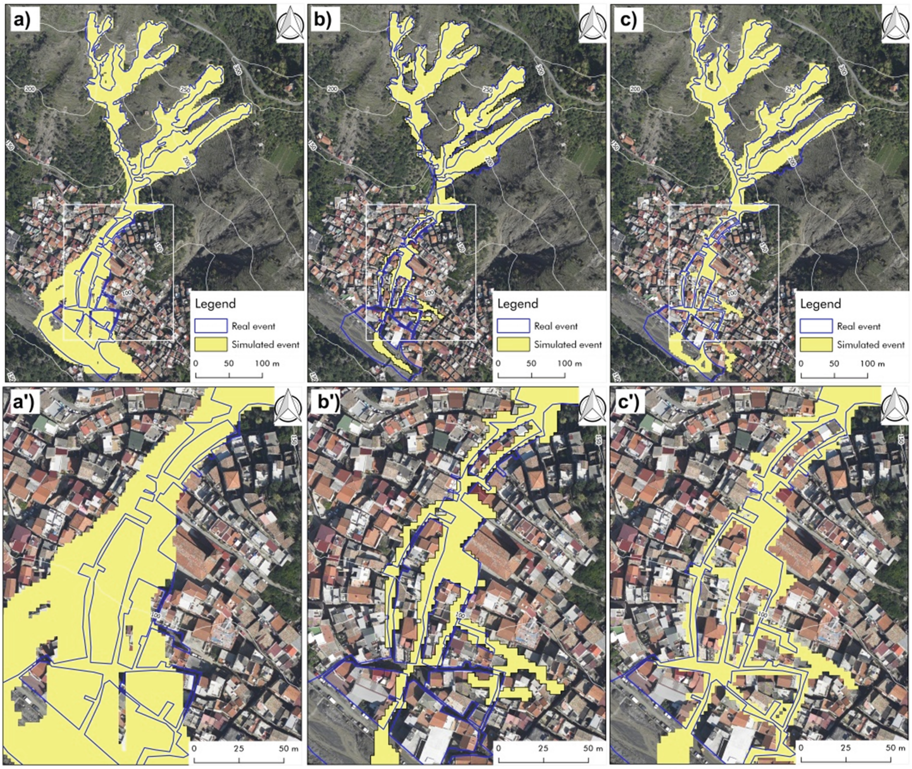

Fig. 2. (a) simulated event on DTM; b) simulated event on DEM; c) simulated event considering the improvement introducing in SCIDDICA; (a′), (b′) and (c′) enlargement of urban area

from simulation. This is related to both the inevitable approximation errors in the process of data elaboration from square cells to hexagonal cells, and to DEM accuracy. The presence of buildings in urban areas involves a greater difference of elevation between the ground and the same buildings, for the same corresponding cell. It induces an approximation in the assessment of the average elevation of cells that are partially covered by a building and by a terrain or a street. Results show that the program could be refined in the reproduction of debris flow propagation into highly urbanized areas, where streets are narrow.

The third experiment, regards this improvement just as described in the preceding paragraphs (cfr. Sect. 2). The improvement was been obtained by a better cell discretization. It allows a better positioning. It is possible to note (Fig. 2 c and c′) as the path of flows is better represented in urbanized areas, compared to the previous cases and to real event. The flows, which inundate the urban area, follow the path of the roads; the simulated travel times improve, resulting much closer to the realty; the real event lasted 5-6 min, case 2 length is 10 min, case 3 length is 7 min.

In Table 5 are reported the values of the evaluation (or fitness) function *e*, where *R* is the set of cells involved in the real event and *S* the corresponding one for simulated event. This function returns values from 0 (completely wrong simulation) to 1 (perfect match); values greater than 0.7 (precision lack in input data) are considered good results. Note how the match is increased in the urban path after the optimization of the model. If we consider only the urban sector, the evaluation function rises from 0.82 to 0.91 (Table 5). The evaluation formula accounts for necessity to compare results of different dimensions, so square (cubic) root normalizes surface (volume) measures.

Table 5. Evaluation function in study area

Case	$e = \sqrt{\frac{R \cap S}{R \cup S}}$ complete event	$e = \sqrt{\frac{R \cap S}{R \cup S}}$ just urbanized area
1	0,73	0.49
2	0,77	0.71
3	0,82	0.91

SCIDDICA is a semi-empirical model, whose parameters are fixed almost definitively in validation phase with the "equivalent fluid" hypothesis [5, 7–9, 19]. Its simulations may be compared with other simulations of the same event, which are performed by the continuous models FLO-2D and TRENT-2D [20].

FLO-2D is a commercial code, adopted worldwide for debris flow phenomena modelling and delineating flood hazards. It is a pseudo 2-D model in space which adopts depth-integrated flow equations. Hyperconcentrated sediment flows are simulated considering the flow as a monophasic non-linear Bingham fluid. The basic equations implemented in the model consist mainly of the continuity equation; in FLO-2D the bed is fixed and all the debris mass is initially available (the erosion is not considered) [20]. Larger Giampilieri areas are covered in FLO-2D simulations in comparison with the real event and SCIDDICA results.

TRENT-2D is a code developed for the simulation of hyperconcentrated sediment transport and debris flows. It is based on a two-phase approach, in which the interstitial fluid is water and the granular phase is modelled according to the dispersive pressure theory of Bagnold, applied to the debris flows. The reference model has a more specific physical base, it is biphasic and able to reproduce the erosion and deposition processes [20]. Small areas, which were invaded in the real event and in SCIDDICA simulation, result untouched in TRENT-2D simulation and vice versa.

SCIDDICA simulations start from detachment area and continue considering erosion before town invasion; results about this first phase lack for both the results of FLO-2D and TRENT-2D.

4 Conclusions

This paper presents SCIDDICA-SS2 improvements for simulating the part of debris flows that invade the urban areas. The less precision, related to momentum, of this version in comparison with SCIDDICA-SS3 and LLUNPIY does not worse simulations in urban areas, because there is a larger turbulence.

Validation has been carried out by simulating Sopra Urno debris flow occurred on October 1st, 2009 in the Giampilieri Superiore territory.

An accurate study was performed in order to obtain the most accurate reproduction of the observed event. In AMD is introduced a new sub-state, which encodes building data, so as to take into account the cells that contain buildings and soil simultaneously. This means that elements at different heights coexist in the same cell. Such model extension adapts very well to this problem. In fact, simulation results of Giampilieri Superiore debris flows are first-rate and may be evaluated still better, because fitness function was applied to the full area of the partially flooded cells.

A comparison with "continuous" models was performed: Flo-2D simulations involve invasion of a very larger area than real event [20]; TRENT-2D approximate well the real event in urban area, which is comparable with SCIDDICA simulations [20].

AMD needs to be improved for flow determination when the building parts of two adjacent cells occupy a common edge. Future work will solve such a minor problem. Another important goal is modelling situations, where part of debris flows runs into tunnels (or channels modified in tunnels) cross the urban area.

The new features of SCIDDICA-SS2 could be very important for hazard and risk analyses in threatened towns by flow-like landslides after a calibration of its parameters on real events, occurred in their territory. Giampilieri area was cultivated until recently, according to agricultural techniques (fine terracing and control of water runoff), introduced during the "Saracen" dominion. The abandonment of the land cultivation and of this cultural heritage is enhancing the natural hazard because of soil deterioration, which cannot emerge easily from the physical data, but can be better captured by empirical parameters, tuned in simulation phase of real events.

The efficiency of possible hazard mitigation works could also be tested by simulations, but solutions have to be evaluated on long times, because the risk (e.g. dams) could be transferred onto future events.

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