Final Sediment Outcome from Meteorological Flood Events: A Multi-modelling Approach

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Abstract. Coastal areas are more and more exposed to the effects of climatic change. Intense local rainfalls increases the frequency of flash floods and/or flow-like subaerial and afterward submarine landslides. The overall phenomenon of flash flood is complex and involves different phases strongly connected: heavy precipitations in a short period of time, soil erosion, fan deltas forming at mouth and hyperpycnal flows and/or landslides occurrence. Such interrelated phases were separately modelled for simulation purposes by different computational models: Partial Differential Equations methods for weather forecasts and sediment production estimation and Cellular Automata for soil erosion by rainfall and subaerial sediment transport and deposit. Our aim is to complete the model for the last phase of final sediment outcome. This research starts from the results of the previous models and introduces the processes concerning the demolition of fan deltas by sea waves during a sea-storm and the subsequent transport of and sediments in suspension by current at the sea-storm end and their deposition and eventual flowing on the sea bed. A first reduced implementation of the new model SCIDDICA-ss2/w&c1 was applied on the partial reconstruction of the 2016 Bagnara case regarding the meteorological conditions and the flattening of Sfalassà's fan delta.

Keywords: Extreme event · Flood · Sediment transport and deposition · Subaerial and subaqueous flow-like landslide · Modelling and simulation

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1 Introduction

Climatic change in coastal areas increases dramatically the frequency of extreme meteorological occurrences, which induce a chain of disastrous events: extremely intense local rainfalls determine heavy soil erosion and can trigger flash floods or debris/mud/granular flows, which, on the shore, can continue as subaqueous debris flows or hyperpycnal flows at mouth of watercourses with the possibility to evolve offshore in density currents. This study is interested in the last part of this composite phenomenon, its evolution from the shoreline toward the open sea.

Different scenarios may be considered: the flood (or the debris flow) that reaches the sea as a hyperpycnal stream that flows on the sea bed and originates a density current; a delta fan, which was produced by the flood, is demolished by one or more sea-storm events of diverse intensity forming detrital submarine flows, particular meteorological conditions could give rise to the suspension of detrital matter and subsequent deposition, when the waves energy decreases. The overall phenomenon is very complex, its modelling and computer simulation (M&S) can be important in order to forecast the natural hazard and manage risk situations.

Different computational approach were adopted for M&S of the diverse interrelated phenomenological components, e.g. classic PDE approximation methods for weather forecasting [1–3] and sediment production estimation [4]; an alternative computational paradigm, the Cellular Automata, was utilized for M&S of "surface flows" [5], a CA methodology for M&S of complex systems was developed [6–8]. The most interesting models related to the phenomenological aspects of final sediment outcome are treated in several CA studies of M&S: SCIDDICA-ss2 and SCIDDICA-ss3 (Simulations through Computational Innovative methods for the Detection of Debris flow path using Interactive Cellular Automata for subaerial, subaqueous and mixed subaerial and subsequent subaqueous landslides) [9–13], M&S of density currents of Salles et al. [14] which is partially derived by a previous SCIDDICA version, SCAVATU (Simulation by Cellular Automata for the erosion of VAst Territorial Units by rainfall) [15], RUSICA (RUdimental SImulation of Coastal erosion by cellular Automata) [16], M&S of hot mudflows [17]; M&S of long-term soil redistribution by tillage [18]; M&S of soil surface degradation by rainfall [19]. The CA for surface flows [6] may be regarded as a two-dimensions space, partitioned in hexagonal cells of uniform size, the cell corresponds usually to a portion of surface; each characteristic, relevant to the evolution of the system and relative to the surface portion corresponding to the cell, is individuated as a sub-state, the third dimension (the height) features, e.g., the altitude, may be included among the sub-states of the cell; each cells embeds an identical computing device, the elementary automaton (ea), whose input is given by the sub-states of the six adjacent cells, the CA evolves changing the state at discrete times simultaneously, according to the transition function of the ea. The transition function accounts for the dynamics of the system and is compound by a sequence of "elementary" processes.

SCIDDICA-ss2 was selected as a significant base for developing in incremental way a model able to account for the physical processes regarding the final sediment outcome that are not present in SCIDDICA-ss2, but may opportunely be imported by the other models SCAVATU and RUSICA. SCIDDICA-ss2 was validated on the well-known 1997 Albano lake debris flow [10,11], this model accounted for the following processes both in subaerial zones and in subaqueous ones, summing up: determination of debris outflows towards the adjacent cells, altitude, kinetic head, debris thickness variation by detrital cover erosion, kinetic head variation by turbulence dissipation, air-water interface effects on the outflows. SCIDDICA-ss2 is able to reproduce the phenomenology of the debris flows, which overcome the coastline and continue as submarine detrital flows, while the following processes, concerning sea-storm events and their consequences have to be introduced: energy transmission from subaqueous currents and waves to granular matter in suspension, on the sea bed, in the flooded area of the shoreline, processes of transport, suspension and sedimentation of granular matter. SCIDDICA, RUSICA and SCAVATU can consider different type of flowing matter: debris, mud, sand, particles; in order to avoid confusion, the general term granular matter will be adopted, granulometries will be specified if necessary. A partial implementation of this extended model SCIDDICA-ss2/w1 was performed, the 2016 Bagnara flood event was considered for simulation in its very final parts, when the Sfalassà's fan delta [20,21] produced by the flood was demolished during successive sea-storms. A partial reconstruction of this last part, starting from the fan delta positioning and structure together with the meteorological conditions during the sea-storms, permitted to "play" with many possible scenarios in order to examine some possible final sediment outcomes. The paper is organised as follows: next section introduces to the new version of SCIDDICA, Sect. 3 presents the SCIDDICA-ss2/w&c1 partial implementation and the geological setting of the study area, the most interesting simulation results are reported, and finally conclusions are discussed.

2 The Model SCIDDICAss2/w&c1

An outline of the model SCIDDICA-ss2/w&c1 is reported in this section, starting from the original model SCIDDICA-ss2 new sub-states and new procedures are introduced in order to account also for the phenomenology of dispersion of sediments.

2.1 An Outline of the Original Model SCIDDICA-ss2

SCIDDICA-ss2 wants to capture the phenomenology of "surface flow" of granular type, debris, mud and the like in terms of complexity emergence both in subaerial areas and in subaqueous ones, it is able to model flow parting and confluence of flows according to the morphology, soil erosion and so on, it is a two-dimensions hexagonal CA model specified by the quintuple: $<R, X, S, P, \tau>$ where:

- $R = \{(x, y)|(x, y \in \mathcal{Z}) \wedge (0 \leq x \leq l_x) \wedge (0 \leq y \leq l_y)\}$ is the finite surface with the regular hexagonal tessellation, that cover the region, where the phenomenon evolves.
- $X = (0, 0), (0, 1), (0, -1), (1, 0), (-1, 0), (1, 1), (-1, -1)$ identifies the geometrical pattern of cells, which influence any state change of the generic cell, identified as the central cell: X includes the central cell (index 0) and the six adjacent cells (indexes 1, ..., 6).
- S is the set of the ea states, they are specified in terms of sub-states of type ground and flow sub-states.
  - Ground sub-states: A is the cell altitude, D is the depth of soil erodable stratum that could be transformed by erosion in granular matter.
  - Granular matter sub-states: T is the average thickness of granular matter of the cell, X and Y are the coordinates of its barycenter with reference to the cell center, and K is its kinetic head.
  - Flow sub-states: ${}^iE$ is the part of outflow, the so called "external flow" (normalised to a thickness), that penetrates the adjacent cell i, $1 \leq i \leq 6$, from central cell, ${}^iX_E$ and ${}^iY_E$ are the coordinates of its barycenter with reference to the adjacent cell center, ${}^iK_E$ is its kinetic head, (six components for each sub-state); ${}^iI$ is the part of outflow toward the adjacent cell, the so called "internal flow", (normalized to a thickness) that remains inside the central cell, ${}^iX_I$ and ${}^iY_I$ are the coordinates of its barycenter with reference to the central cell center, ${}^iK_I$ is its kinetic head, (six components for all the sub-states).
- P is the set of the global physical and empirical parameters of the phenomenon, they are enumerated in the following list and are better explicated in next section: p_a is the cell apothem; p_t is the temporal correspondence of a CA step; p_{adhw}, p_{adha} are the air/water adhesion values, i.e. the landslide matter thickness, that may not be removed; p_{fcw}, p_{fca} are the air/water friction coefficient for the granular matter outflows; p_{tdw}, p_{tda}, p_{fcw}, p_{edw}, p_{eda} are air/water parameters for energy dissipation by turbulence, air/water parameters for energy dissipation by erosion; p_{ml} is the matter loss in percentage when the landslide matter enters into water; p_{mtw}, p_{mta} are the air/water activation thresholds of the mobilization; p_{erw}, p_{era} are the air/water progressive erosion parameters; p_{wr} is the water resistance parameter.
- $\tau : S^7 \rightarrow S$ is the deterministic state transition for the cells in R, basic processes of the transition function are here sketched, note that ΔQ means variation of the ground sub-state Q, ground sub-state Q of the adjacent cell i, $1 \leq i \leq 6$, is specified as Q_i; the subscripts "w" and "a" in parameter names are omitted, when the formula is considered valid both in water and air.
- Mobilization Effects. When the kinetic head value overcomes an opportune threshold ($K > p_{mt}$), depending on the soil features and its saturation state, a mobilization of the detrital cover occurs proportionally to the quantity overcoming the threshold: $p_{er}(K - p_{mt}) = \Delta T = -\Delta D = -\Delta A$ (the detrital cover depth diminishes as the granular matter thickness increases), $-\Delta K = p_{ed}(K - p_{mt})$ calculates the kinetic head loss.

- Turbulence Effect. The effect of the turbulence is modelled by a proportional kinetic head loss at each SCIDDICA step: $-\Delta K = p_{td}K$.
- Granular Matter Outflows. The computation of the outflows f_i, $0 \leq i \leq 6$ from the central cell toward the cell i (f_0, is the quantity that does not flow) is performed in two steps: determination of the outflows minimizing the differences of "heights" h_i, $0 \leq i \leq 6$ in the neighborhood by the "algorithm of minimization of differences" [5,6], and computation of the shift of the outflows with subsequent determination of external and internal outflow sub-states.
  First step: The quantity d to be distributed from the central cell: $d = T - p_{adh} = \Sigma_{0 \leq i \leq 6} f_i$. "Heights" are specified as: $h_0 = A + K + p_{adh}$; $h_i = A_i + T_i$, $0 \leq t \leq 6$; the values of flows are obtained in order to minimize $\Sigma_{0 \leq i < j \leq 6}(|(h_i + f_i) - (h_j + f_j)|)$.
  Second step: The s_i shift of f_i with slope θ_i related to heights h_i, h_0 $0 \leq i \leq 6$ is modelled as the body barycentre's movement on the slope:
  $s_i = v_i + p_t + g(\sin\theta_i - p_{fca}\cos\theta_i)p_t^2$, with g the gravity acceleration and initial velocity $v_i = \sqrt{2gH}$ in the subaerial case;
  $s_i = (1 - exp(-p_{wr} \cdot p_t))v_i \cdot p_t + g\prime(\sin\theta_i - p_{fcw} \cdot \cos\theta_i\ p_{wr})) + g\prime(\sin\theta_i - p_{fca} \cdot \cos\theta_i)p_t/p_{wr}$, the water resistance is considered for the subaqueous case, a modified Stokes equations, it is adopted with a form factor proportional to mass and $g\prime < g$, accounting for buoyancy.
- Flows Composition. The new values of the ground and granular matter sub-states are calculated according to the new values of flow sub-states.
- Air-Water Interface. An external flow from an air cell (altitude higher than water level) to a water cell (altitude lower than water level) can imply a loss of matter (water inside debris and fine grains) proportional to debris mass, specified by p_{ml}; it implies a correspondent loss of kinetic energy, determined by kinetic head decrease.

At the beginning of the simulation, we specify the states of the cells in R, defining the initial CA configuration. The initial values of the sub-states are accordingly initialized. In particular, A assumes the morphology values except for the detachment area, where the thickness of the landslide mass is subtracted from the morphology value; T is zero everywhere except for the detachment area, where the thickness of landslide mass is specified; D assumes initial values corresponding to the maximum depth of the mantle of soil cover, which can be eroded. All the values related to the remaining sub-states are zero everywhere. At each next step, the function τ is applied to all the cells in R, so that the configuration changes in time and the CA evolution is obtained.

2.2 Outline of the Preliminary Version of SCIDDICA-ss2/w&c1

SCIDDICA-ss2/w&c1 is a two-dimension hexagonal CA model, extension of SCIDDICA-ss2, which is specified by the septuplet:

$<R_{w\&c1}, G_{w\&c1}, X_{w\&c1}, S_{w\&c1}, P_{w\&c1}, \tau_{w\&c1}, \gamma_{w\&c1}>$ where:

- $R_{w\&c1} = R$
- $G_{w\&c1}$ is the set of cells, which undergo to the influences of the “external world”; in this case, they are the “underwater” cells, which are exposed to the effect of the waves.
- $X_{w\&c1} = X$
- $S_{w\&c1}$ is the set of the ea states, they are specified in terms of sub-states of type ground, granular matter and flow sub-states. This model has to account layers of matter of different granularity (n layers) and sub-states, related to waves and currents.
  - Ground sub-states are the same as in SCIDDICA-ss2.
  - Granular matter sub-states for each layer j, $1 \leq j \leq n$: T_j is the average thickness of granular matter of the cell, X_j and Y_j are the coordinates of its barycenter with reference to the cell center, K_j is its kinetic head; S_j is the granular matter of layer j in suspension in the cell, normalized to a thickness.
  - Flow sub-states for each layer $j, 1 \leq j \leq n$: ${}^iE_j$ is the part of outflow, the so called “external flow” (normalized to a thickness), that penetrates the adjacent cell $i, 1 \leq i \leq n$, from central cell, ${}^iX_{Ej}$ and ${}^iY_{Ej}$ are the coordinates of its barycenter with reference to the adjacent cell center, ${}^iK_{Ej}$ is its kinetic head, (six components for each sub-state); ${}^iI_j$ is the part of outflow toward the adjacent cell, the so called “internal flow”, (normalized to a thickness) that remains inside the central cell, ${}^iX_{Ij}$ and ${}^iY_{Ej}$ are the coordinates of its barycenter with reference to the central cell center, ${}^iK_{Ij}$ is its kinetic head, (six components for all the sub-states); ${}^iS_j$ is the part of suspended matter outflow (normalized to a thickness), that penetrates the adjacent cell $i, 1 \leq i \leq 6$, from central cell, ${}^iX_{Sj}$ and ${}^iY_{Sj}$ are the coordinates of its barycenter with reference to the adjacent cell center.
  - Wave and current sub-states: A_w, the wave amplitude; L_w, the wave length; X_w, Y_w, component $x - y$ of wave direction; the $C_x, C_y, x - y$ speed components of the surface current.
- $P_{w\&c1}$ is the set of the global physical and empirical parameters of the phenomenon, there are the same parameter of P except p_{adhw}, p_{adha} the air/water adhesion values and p_{adhw}, p_{adha} the air/water friction coefficient for the granular matter outflows; they are multiplied because take a different value for each layer $j, 1 \leq j \leq n$: ${}^jp_{adhw}, {}^jp_{adha}$. Parameters, regarding the wave demolition of the layers, are the activation thresholds of the mobilization ${}^jp_{mt}$ (${}^jp_{mts}$ for the suspension dynamics at the shoreline) and the progressive erosion parameters ${}^jp_{er}$ (${}^jp_{ers}$ for the suspension dynamics at the shoreline) for each layer $j, 1 \leq j \leq n$.
- $\tau_{w\&c1}$, contains all the elementary processes of τ, they are applied to each layer according to proper sub-states and parameters; furthermore the following processes are considered with only a type of granulometry for simplicity sake in the exposition:
  - Suspension by erosion for cells at the shoreline. When the wave amplitude overcomes an opportune threshold ($A_w > {}^1p_{mts}$), depending on the layer

features, a mobilization of the layer occurs proportionally to the quantity overcoming the threshold: ${}^1p_{ers}(A_w - {}^1p_{mts}) = \Delta S_1 = -\Delta T_1$ (the layer's thickness diminishes as the matter in suspension increases). Note that deposit process can follow immediately to the suspension process at the shoreline.

- Suspension, deposit and deposit mobilization processes. These processes derive from the model RUSICA [16,21], but they are adapted to the phenomenological conditions of the sea storm: matter in suspension can be increased by deposit erosion depending on the energy on the bottom sea: ${}^1p_{ers}(e_b - {}^{-1}p_{mts}) = \Delta S_1 = -\Delta T_1$, where e_b is the energy at the bottom sea; the wave energy inside a cell e_c can maintain granular matter in suspension until a maximum density $d_{mx} = p_{mt}(e_c - p_{mne})/(-A)$ depending on granulometry of the matter, otherwise precipitation of a part of suspended matter occurs until the equilibrium is reached: $\Delta T_1 = -\Delta S_1 = S_1 - Ad_{mx}$.
- Diffusion of the granular matter in suspension during a sea storm. A diffusion mechanism, using the "algorithm of minimization of differences" [5,6], is adopted, it is similar to that of the previous section, a value of K_1 depending on the wave sub-states is introduced and A (value of central cell) is considered constant in the neighborhood, because there is no slope for matter in suspension, but only differences in density.
- Transport of the granular matter in suspension by sea currents. The shift s is specified as $s = p_t\sqrt{(C_x^2 + C_y^2)}$, originating for the granular matter in suspension, the outflows ${}^iS_1$ toward the adjacent cells according the Θ angle of the current such that $\Sigma^i_{1\le i\le 6} S_1 = S_1 \cdot s/p_a$. The slow deposition process of granular matter transported by current is not considered.

– $\gamma_{w\&c1}$ is the external influence function, that returns step by step ($\mathcal{Z}$) the significant values regarding waves and currents, it is split in the following functions:
– $\gamma_w : \mathcal{Z} \times G_{w\&c1} \rightarrow A_w \times L_w \times X_w \times Y_w$ for generation of wave values cell by cell of $G_{w\&c1}$ according to the observations or meteorological forecasting.
– $\gamma_c : \mathcal{Z} \times G_{w\&c1} \rightarrow C_x \times C_y$ for generation of current values cell by cell of $G_{w\&c1}$ according to the observations or meteorological forecasting.

SCIDDICA-ss2 and RUSICA coalesce with strong simplifications in this preliminary version w&c1; layers of different granulometry are here considered separately, but phenomenological conditions of their possible innermost mixing are tackled superficially and need simulations of real events in order to improve the model by an accurate parametrization or introducing new sub-states, parameters and elementary processes according to the methodology of incremental CA modelling, furthermore the model is "cut" for reduced applications.

3 Examples of Simulation of Demolition Process of Fan Delta by Sea-Storm and Sediment Outcome: The 2015–16 Sfalassà Case

A summary of observation of demolition of fan delta by sea storms precedes in this chapter the section specifying the partial implementation of SCIDDICA-ss2/w&c1; the simulations of the demolition of the 2015 fan delta follow, at the end, an hypothetical case of transport in suspension was simulated.

3.1 Summary of Observations Related to the Sfalassà's Area and Meteorological Events

The interested area is characterised as follows: the wide of continental shelf varies from 120 m north of Marturano Promontory to 50 m at Cacili promontory. It reaches the maximum extension, about 300 m, at south of Marturano Promontory and narrows to about 100 m in the area close to Sfalassà's mouth to become again wider (about 180 m) southward (Calabria, Italy). The continental shelf has a slope $\leq 7°$, it continues with a continental slope that between 20 m and 50 m depth has a slope range of 20°–30°, that becomes of 10°–20° at higher depth. The submarine retrogressive scars confined at canyon head-walls coincide with both Sfalassà and Favazzina fiumara mouth. The emerged beach has a height varying between 0 and 3.5 m a.s.l. and a mean slope of 6° in accordance with the slope of continental shelf. The volume of fan delta, grown in consequence of flood event occurred on 2 November 2015 is of about 25.000 m^3 this value is in agreement with the volume of fan delta formed in consequence of flood events and the evaluation of yield sediment derived from EPM model [24].

From a meteorological point of view, the flood event was analyzed in detail in a recent work [23], where different configurations of a mesoscale atmospheric model were tested and several sensitivity tests were carried out. The precipitation affected principally the eastern side of the Calabria, although huge quantities of rain have been recorded on the southerly Tyrrhenian areas. An upper level trough over Sicily, synergistically to a low-pressure area at the surface, favored the advection of moist and warm air masses from the Ionian Sea towards the eastern side of the Calabria. Considering the observed precipitation collected by regional network of the "Centro Funzionale Multirischi" (http://www.cfd.calabria.it), it can be seen how several rain gauges recorded precipitation >500 mm for the whole event, some of which just located on the western slopes of the Aspromonte Mountain, upstream to the Sfalassà's area. The rain gauge of Bagnara Calabra recorded 96 mm on 31 October and 112 mm on 1 November, demonstrating the extraordinariness of the event. Consequently to flood a significant fan delta was formed at the mouth of Sfalassà watercourse by detrital matter consisting of badly classified sediments from coarse sand 0.75 mm to blocks of 1.0 m, an average value of 150 mm may be considered. The thickness of this fan delta is approximately 5 cm in average, surface of the underwater detrital cover, until the original coastline, was estimated 9250 m^2. Meteo-marine

Fig. 1. Interested area of Bagnara site and sequence of photographs showing effect of flash-flood and sea storms

events (at least three strong sea storms) occurred during the period 2015.11.25 to 2016.01.28, they brought to destroy almost completely the fun delta. The first sea storm (general information in Table 1st event) took away a thin strip of the delta fan parallel to the beach, the stronger second sea storm (general information in Table 2nd event) took away a larger strip of the delta fan parallel to the beach, the last strongest sea storm (general information in Table 3rd event) demolished the delta fan.

Regarding the storms, a marine-waves analysis was carried out. For the case we considered high-resolution ($0.125° \times 0.125°$) simulations carried out with the model WAM (WAve Model), developed by ECMWF (European Centre for Medium-Range Weather Forecasts). The sea storms are classified reporting in the tables the most significant marine parameters:
SWH (Significant wave height [m]); MWP (Mean wave period [s]); MWD (Mean wave direction [degrees]); $PP1D$ (Peak period of 1D spectra [s]); $HMAX$ (Maximum individual wave height [m]); $TMAX$ (Period corresponding to maximum individual wave height [s]).

Table 1. Extreme events after flash flood occurred ranging November 2015 January 2016 here statistic values regarding model output WAM for the three entire period

	ESWH (m)	MWP [s]	MWD [degrees]	PP1D [s]	HMAX [m]	TMAX [s]
25–28/11/2015						
MAX	1,85	6,52	297,92	7,43	3,59	5,90
MIN	0,98	5,80	266,58	6,19	1,88	4,80
AVE	1,32	6,24	283,30	6,62	2,55	5,62
std	0,26	0,18	10,88	0,40	0,53	0,22
03–08/01/2016						
MAX	2,11	7,43	294,29	8,73	4,01	6,74
MIX	1,00	4,75	265,76	6,13	1,93	4,33
AVE	1,48	6,64	283,30	7,41	2,85	5,94
std	0,40	0,33	4,53	0,99	0,76	0,31
12–18/01/2016						
MAX	2,43	7,62	317,07	9,06	4,63	6,82
MIX	0,89	5,32	275,50	6,17	1,69	5,07
AVE	1,53	6,60	294,97	7,71	2,92	5,93
std	0,43	0,56	12,17	0,87	0,81	0,43

The values are extrapolated by the full gridded output of WAM, in particular at an offshore position located about 3 km away from the coastline. Such values opportunely simulated with near-shore model amplify the effect especially for the waves height. These parameters, for the different sea storms, are taken into account for the SCIDDICA simulations.

The Table 1 shows considered events, according periods, reporting statistical values for the entire storm.

The effect of sea storms may be deduced roughly by a series of photographs of the area after the sea storms (see Fig. 1).
The most realistic scenario of the event considers that the strength of the waves did not allow for suspension the matter, that constituted the fan delta because of its granulometry, so granular matter, that was eroded by the strength of the waves, flowed on the seabed without be significantly influenced by the currents [22].

3.2 Partial Implementation of SCIDDICA-ss2/w&c1 and First Simulations

Implementation of SCIDDICA-ss2/w&c1 was performed on the previous one of SCIDDICA-ss2 in language C++, introducing partially and adapting sub-states, parameters and processes of RUSICA. An important limit regards the granulometry of granular matter, there is only a layer, corresponding to the fan delta, whose granulometry is an "equivalent" granulometry of a mixture of deposits.

This could be a solution in some cases, but it is not always satisfying, particularly when a very heterogeneous granulometry could involve both suspension and flowing on the sea bed. The aim of this first version is to test the model according phenomenological view-point, i.e. if the elementary processes account for the main mechanisms of the overall phenomenon. Two cases are considered, the real case of demolition of the fan delta by successive sea storms of different intensity and the very hypothetical case of a sea storm in the same area, but with suspension: if the granular matter would be very fine, the sea storm could cause diffusion in suspension, then it could be transported by the currents at the end of the sea storm. Note that the model provides for an adherence effect, i.e. a smallest part of matter remains always in the cell (less than 1 mm) and cannot be transported outside the cell; it permits to mark the flows.

3.3 Simulation of the Demolition of the 2015 Fan Delta of Watercourse Sfalassà

Three sea storms are considered after the 2015 flash flood in the Bagnara area that formed the fan delta Fig. 1. The first sea storm in the Table 1 is the shortest lasting and lesser sea storm. It does not weight much, only a thin part facing the sea of the fan delta is eroded and a small flow of the eroded part is channelized toward the offshore depression; only a minimum quantity reaches it (Fig. 2b).

Simulation of the second sea storm starts from the final conditions immediately after the first sea storm. The considered second storm 1 is longer and stronger than the first one, it effects the central area of the fan delta; a subaqueous flow of granular matter begins to reach the depression (Fig. 2c).

Simulation of the third sea storm in Table 1 starts from the final conditions immediately after the second sea storm. This sea storm is the longest and strongest, the fan delta is destroyed except two small parts on the right and on the left (Fig. 2d). Almost all the matter, that formed initially the fan delta, reached the sea depression. The global evolution of the system in the simulation reproduces significantly the real event: the erosion propagates progressively from the water line to the internal fringe area.

3.4 A Very Hypothetical Case of Transport in Suspension

In Fig. 2 simulation steps of erosion of the Sfalassà's fan delta and resulting subaqueous flows of the eroded granular matter, thickness of granular matter is reported: (a) initial erosion of the fan delta (initial conditions), (b) effect at the end of the first sea storm corresponding approximately to 3 days and 6 h, (c) effect at end of the second sea storm approximately with duration of 5 days and 12 h, (d) third storm (duration of 6 days and 21 h) dismantling delta fun i.e. area until original coastline.

Regarding the calibration phase of parameters, the main effort regarded this new part of model, i.e., the elementary process (suspension, deposit and deposit mobilization) concerning the demolition of the fan delta; a simple trial and error

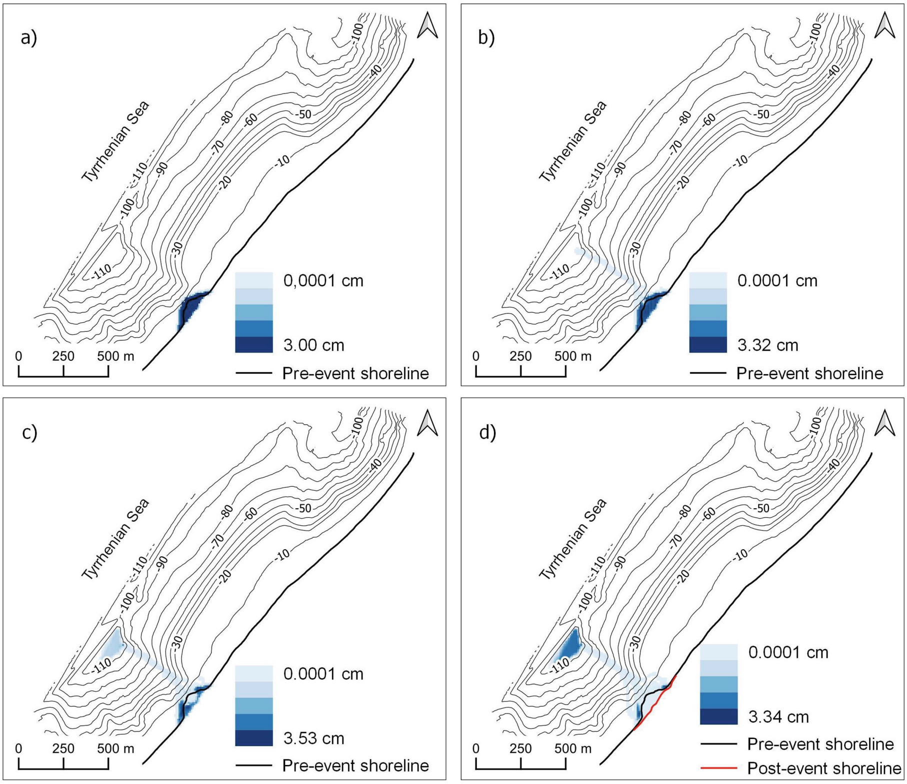

Fig. 2. Simulation steps of erosion of the Sfalassà's fan delta and resulting subaqueous flows thickness: (a) step 1, initial erosion, (b) step 1350: end of the first sea storm, (c) step 3550: end of the second sea storm approximately, (d) step 6300: the third sea storm dismantling of the delta fun.

method was possible to be applied with satisfying results in comparison with the partial reconstruction of the real case.

The second case consider a hypothetical sea storm on a not-realistic fan delta as far composition in comparison with real case, its granulometry permits the suspension after the delta demolition, after the sea storm, a constant current intercepts the granular matter and transported it.

Initial position of the fan delta is the same as in the previous case, of course with a different thin granulometry. The effect of the sea storm is just a diffusion of the eroded granular matter in suspension (step 1000 of the simulation, (Fig. 3a). The sea storm ceases at the step 2500, the further erosion at the step 2000 is reported in the Fig. 3b).

After the sea storm, a hypothetical (and not realistic) current effected the suspended granular matter and channelizes it in its direction, toward NE. The transport path is reported clearly in (Fig. 3a) (step 3000, 500 steps of the trans-

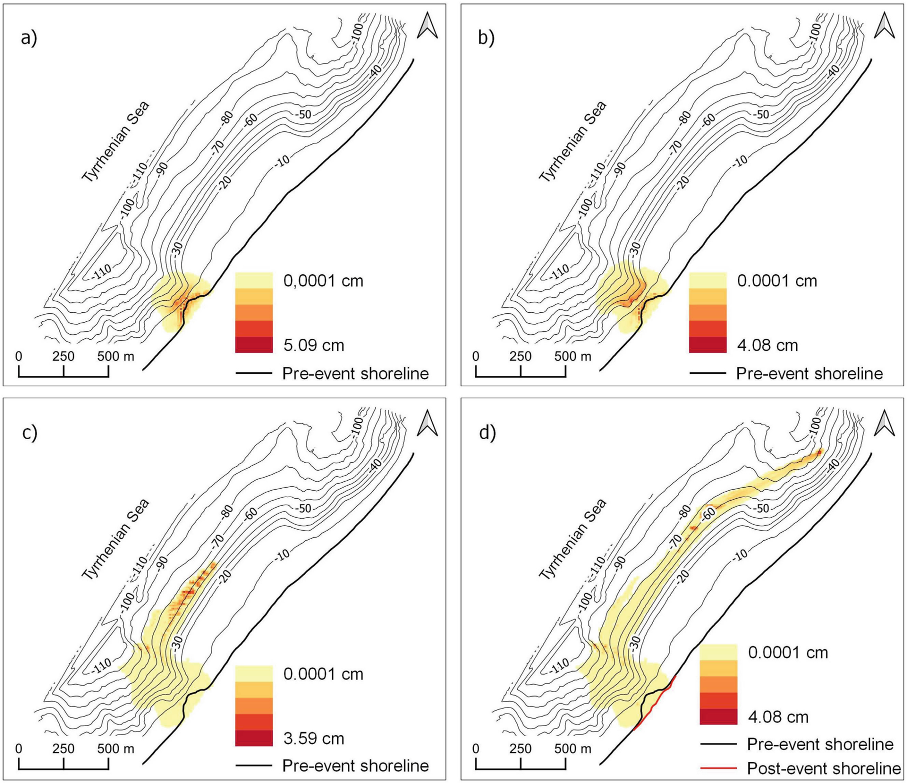

Fig. 3. Simulation steps of hypothetical diffusion in suspension of the eroded granular matter of the fan delta: (a) step 1000, (b) step 2000, (c) step 3000, (d) step 4000.

port in suspension). The last (Fig. 3d) step 4000 shows as the path continues to be channelized in NE direction. Such a current does not exist and its distance from the coast is improbable, but bathymetry data at disposal don't permit to see the evolution of the simulation for a sufficient space in order to evaluate the model in the case of another direction of current; that is the reason so unnatural distance from the coast has been hypothesized.

Regarding the calibration phase of parameters, a simple trial and error method was satisfying for the elementary processes concerning diffusion, suspension and transport of granular matter for a hypothetical (not real) case.

The main effort regarded this new part of model, i.e., the elementary process (suspension, deposit and deposit mobilization) concerning the demolition of the fan delta; a simple trial and error method was possible to be applied with satisfying results.

4 Conclusions

SCIDDICA-ss2/w&c1 was defined on the base of two models CA model SCIDDICA-ss2, that is a well-founded model, very successful for a large range of applications and RUSICA still in a phase of development. Such a model is very complex and our effort was the inclusion and refinement of elementary processes for harmonizing the two models and introducing new features according the incremental modelling method for macroscopic CA. Therefore, the implementation of the model was partial in order to focus itself on the phenomenology in a first rough way and understand the factors that permit a correct emergence of the overall phenomenon. This partial and rough implementation of SCIDDICA-ss2/w&c1 was applied on a real case, whose data for simulation are incomplete and approximate and on a hypothesized case, which isn't realistic, considering the geological characteristics of the same area of the first case, but interesting for a comparison of the different behaviours in the same initial context. The development of the simulated event in the first case may be considered successful in the limits of the implementation if we consider the demolition of the fan delta by the succession of the sea storms thanks to a good knowledge of meteorological data. The final outcome of the sediments is correct but times for a complete deposit in the depression could be different. About, the second case, the initial diffusion in suspension of eroded matter of fan delta and the transport by current was simulated satisfactory obviously only from a phenomenological viewpoint, a real case with enough precise data is necessary for correcting and improving the model. This is just a preliminary step. Further work and effort has to be pursued in order to better outperform the model and its results due to presence of several parameters necessary to describe a macro complex system such as this and with a huge and long time involved area. In these case it is necessary to obtain detailed and long term data to define better the parameters values interval and consequently obtain a more precise pattern of sediments distribution.

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