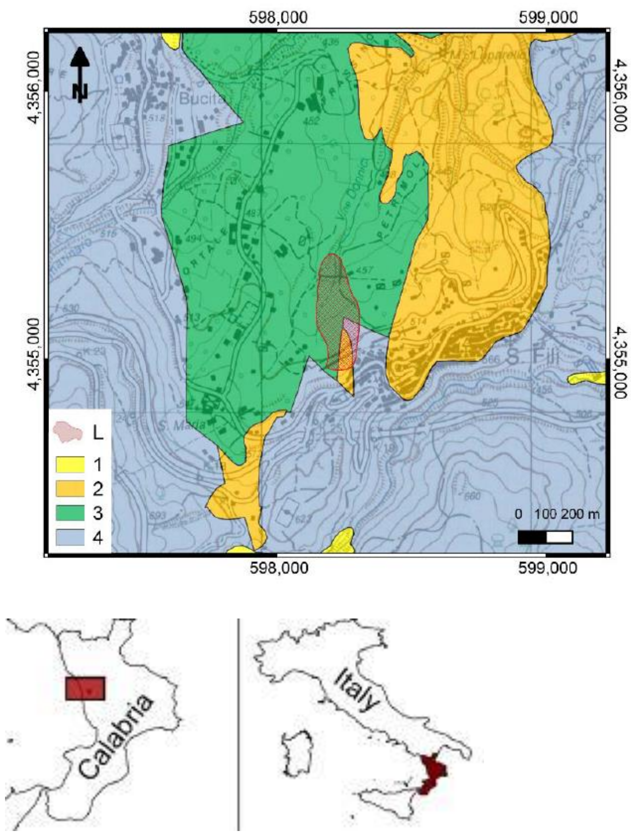
Appendix B

An example of application[1]

The Uncino rock slide (Figure B-1) is located along the NW margin of San Fili (ca. 500 m a.s.l.), in the Crati graben, Northern Calabria (Italy). In the area, Palaeozoic weathered metamorphic rocks (migmatitic gneiss and biotitic schist) are mantled by late Miocene conglomerate, arenite and marly clay, and by Pliocene-Quaternary sand and clay. The landslide mainly involved Miocene clay and subordinate sandstone, overlaying the metamorphic bedrock, with a length of 650 m, a width of 200 m, and an estimated depth of 25-30 m (Terranova et al., 2018). In historical time, several reactivations were recorded that damaged to the outskirts of San Fili, the railway and the local road network. The mobilization dates considered in this study refer to the period 1960-1980 (Table B-1), due to data accuracy and availability of rains, even if the oldest notices of activation date back to the beginning of the past Century.



[1] For more details, please refer to: De Rango A, Terranova A, D'Ambrosio D, Lupiano V, Mendicino G, Terranova OG, Iovine G (submitted). GA SAKe-2.0 – An advanced hydrological model to predict the activation of landslides.

Figure B-1 – Lithological sketch of the Uncino landslide. Key) 1) Alluvium, colluvium, and residual soil; 2) conglomerate and sandstone; 3) Clay and clayey flysch; 4) Medium-high grade metamorphic rock. The landslide (L) is marked by a red hatched polygon. Lithological map after Geological map of Calabria - scale 1:25,000 (CASMEZ, 1967), mod. On bottom, the location map.

#	**activation date**
1	16.01.1960
2	01.11.1962-14.04.1963
3	15.04.1964
4	14.12.1966
5	13.02.1979
6	*December 1980*

Table B-1 - Uncino landslide: dates of activation used for calibration (#1-5) and validation (#6) - after Iovine et al., 2017; Terranova et al., 2018.

The closest rain gauge is located at Montalto Uffugo (468 m a.s.l.), about 8 km north of San Fili. In the area, the climate has quite marked seasonal characteristics, with a wet season of about 6 months (October-March) and the rest of the year drier (Terranova and Iaquinta, 2011). The daily rain series employed for calibration range from 1 September 1959 to 31 August 1980 (i.e., from the beginning of the hydrological year including the first activation date, to the end of the hydrological year antecedent to the validation date). On the other hand, the daily rain series employed for validation starts from 1 September 1980 (i.e., in continuity with the previous series) and stops on 31 March 1981 (at the end of the last rainy season, including the validation date).

B.1 - Model initialization, calibration and sensitivity

Starting from the *benchmark* configuration employed in (Terranova et al., 2015), based on previous experiences, a set of calibration experiments were performed to exploit the new features of ^{GA}*SAKe-2.0*, and to preliminarily evaluate its sensitivity. To this purpose, activation dates #1-5 in Table B-1, and daily rains from 1st September 1959 to 31 August 1980 (as recorded at the Montalto Uffugo rain gauge) were used. Adopted values of GA parameters are listed in Tables B-2 and B-3. In addition, the following *operational parameters* were adopted: number of processors: 4; seed: 1; frequency of kernel saving (iterations): 100; number of best kernels to be saved (*Nbk*): 100.

Symbol	GA Parameter	values
i_{max}	maximum number of iterations	4000, 6000, 8000, **10000**, 12000, 14000, 16000, 50000, 100000
N	Population size (Individuals of each GA population)	20, **100**
P_c	Crossover probability, in the range [0,1]	0.6, 0.65, 0.7, **0.75**, 0.8, 0.85, 0.9
P_m	Mutation probability (of elements height and of *base time*), in the range [0,1]	0.10, 0.15, 0.20, **0.25**, 0.30, 0.35, 0.40
p_{mtb}	Factor defining the range in which d_{tb} is selected	3, 4, **5**, 6, 7
$t_{bMin,}$	t_b minimum value	**15**
t_{bMax}	t_b maximum value	**180**
p_{me}	Number of elements of the kernel to be mutated, expressed as % t_b	15, 20, **25**, 30, 35
p_{dH}	% h_{max}, used to define the range in which dh is selected.	40, 45, **50**, 55, 60

Table B-2 – Uncino landslide: adopted values of GA parameters. Per each parameter, the considered values are shown (*benchmarks* are in bold).

GA Parameter	Option	Condition	Values
Initial shape	Rectangular; **Decreasing triangular**; Increasing triangular; Random;		
Replacement	Generational	-	-
	Elitist/steady state	$1 \leq n_e \leq N$	N = 20, n_e = 4, 6, 8, 10, 12; N = **100**, n_e = **10**, 20, 30, 40, 50
Selection	**Stochastic Tournament**	$0.55 \leq T_r \leq 1$	**0.55**, 0.75, 0.95
	Deterministic Tournament	$2 \leq T_s \leq N$	2, 3, 5
	Ranking	$0 < s < 1$ (exponential); $1 \leq s \leq 2$ (linear)	0.1, 0.5 0.9 1, 1.5, 2
	Roulette	-	-
Fitness	**Hierarchically Weighted (HW)**		
	Equally Weighted (EW)		
	Area Under Curve – Receiver Operator Characteristic (AUC-ROC)	Number of thresholds (n_{tr})	6, 8, 10, 12, 14

Table B-3 – Uncino landslide: additional GA parameters (*benchmarks* are in bold).

Note that a decreasing triangular initial shape was considered by (Terranova et al., 2015) for the kernel of the *benchmark experiment* as, generally, in case of landslides of moderate extent (such as the S. Fili one), “recent” rainfall (i.e. those recorded at or immediately before activation) have greater impact on slope stability with respect to those occurred in the antecedent period. Similarly, the assumed values for t_{bMin} and t_{bMax} were selected by considering the landslide extent and climate characteristics of the study area. The remaining values employed in the *benchmark experiment* are shown in bold in Tables B-2 and B-3.

In Figures A-1 and A-3, the initialization and output masks related to the benchmark experiment are shown. From the first line below the graphs, it can be appreciated that *AMF* is ca. 0.94; it was first obtained at iteration 7411, by a kernel (second line) with t_b = 46 days, Δz_{cr} = 0.0027, μ_0 = 22.888, $z_{j\text{-}min}$ = 16.488, and z_{cr} = 16.444. As for the *ABK* (third and fourth lines), t_b = 46 days, Δz_{cr} = 0.0211, μ_0 = 22.892, $z_{j\text{-}min}$ = 16.804, and z_{cr} = 16.450. The same parameters are also listed for the *best kernel* of the "current" iteration (eight-tenth lines) – note that, in the example, this latter refers to i=10,000, as the image was taken after the end of the prefixed iterations (i_{max} = 10,000). In addition, the average fitness of both the whole population of kernels (fifth line), and of the current population (seventh line) are also shown.

In addition to the decreasing triangular *initial shape*, all the experiments were performed by also considering the rectangular, increasing triangular, and random shapes (keeping unchanged all the other parameters). Furthermore, all the experiments were evaluated by means of HW, EW and AUC-ROC *fitness functions* (this latter, by using n_{tr} = 10, except for 4 experiments in which the number of thresholds varied in the range 6-14, as shown in Table B-3).

As concerns the preliminarily sensitivity analysis, most of the experiments were performed to check model behaviour with respect to its main features (cf. sections 2 to 5 in Figure A-1), starting from the benchmark configuration by varying, one at a time, the model parameters as listed in Tables B-2 and B-3. Moreover, in some experiments, a couple of parameters were changed with respect to the benchmark, as listed below:

- n_e = 20 and T_s = 2, 3, 5;
- n_e = 20 and s = 0.1, 0.5, 0.9, 1, 1.5;
- N = 20 and n_e = 4, 6, 10, 12.

As a whole, 784 runs were performed (totalizing more than 3.7 million of iteration steps), obtaining an average *fitness* of ca. 0.952 and σ = 0.0703. Of these, 244 runs reached the maximum *fitness*, and 400 runs showed *fitness* ≥ 0.999 (cf. Figure B-2). Only 6 runs got *fitness* < 0.75 – as listed in Table B-4.

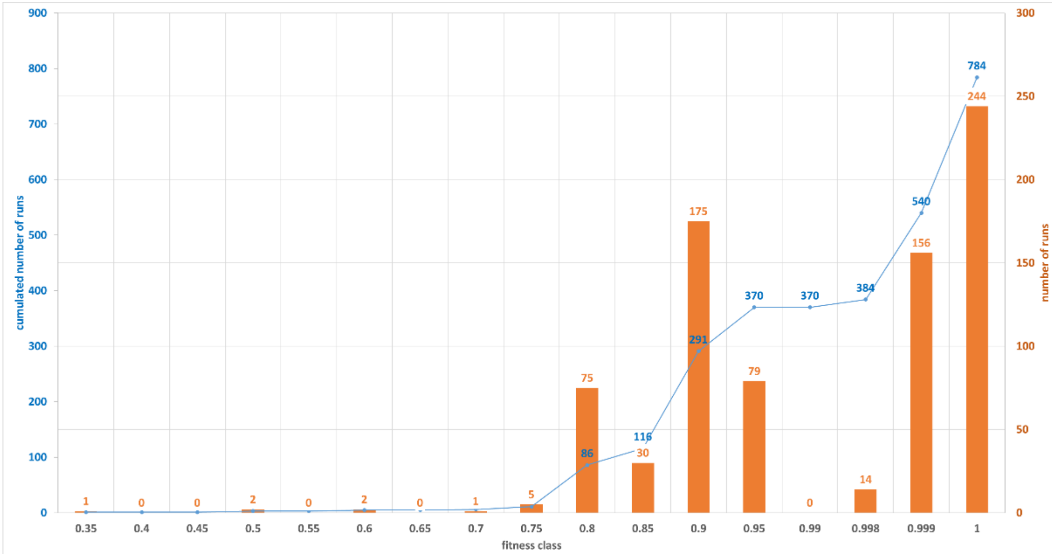


Figure B-2 – Uncino landslide: frequency distribution of obtained *fitness* values. Orange bars show the number of runs with *fitness* values in the class shown in abscissa. The blue line shows the cumulated trend of frequency distribution. Note that class widths shrink for fitness greater than 0.9.

run	*initial shape of the Kernel*	*fitness function*	*N*	*replacement*	*fitness*	Δz_{cr}	t_b	μ_0	*step*
F147	increasing triangular	HW	100	generational	0.719	0.001	46	25.68	91
F151	increasing triangular	EW	100	generational	0.612	0.000	127	52.96	28
F149	decreasing triangular	EW	100	generational	0.604	0.001	143	69.61	6446
F152	random	EW	100	generational	0.521	0.001	34	19.22	32
D158	rectangular	HW	**20**	elitist/steady state **e=10**	0.517	0.003	44	22.00	2
D162	rectangular	EW	**20**	elitist/steady state **e=10**	0.380	0.003	44	22.00	2

Table B-4 – Uncino landslide: worst runs (*fitness* < 0.75).

If considering the 407 runs with *fitness* ≥ 0.998, the average *safety margin* is 0.0234 (st. dev. = 0.0177):

- of these 407 runs, 152 have *safety margin* greater than the average; they have average *base time* = 69 (st. dev. = 21.6);
- of these 152 runs, 100 have *base time* smaller than the average; they have average *first-order momentum* = 27.6 (st. dev. = 2.41);
- of these 100 runs, 57 have *first-order momentum* smaller than the average.

Summing up, such 57 kernels:

- have average number of *steps* = 2648 (st. dev. = 3504), average *safety margin* = 0.043 (st. dev. = 0.012), average *base time* = 53 (st. dev. = 3.8), and average *first-order momentum* = 25.9 (st. dev. = 1.3);
- present fairly homogeneous characteristics (with the sole exception of the number of steps, which, however, does not strongly affect the calculation time). Among them, the best 10 runs ("most efficient" – i.e., those with the smaller number of steps) are listed in Table B-5.

run	*initial shape of the Kernel*	*fitness function*	*"varied" parameter*	*fitness*	Δz_{cr}	t_b	μ_0	*step*
D309	**decreasing triangular**	EW	p_{me} = 30	1.0	0.057	53	26.36	310
F214	rectangular	ROC	P_c = 0.9	1.0	0.053	53	26.54	176
F269	**decreasing triangular**	EW	p_{mtb} = 7	1.0	0.045	53	27.11	250
F208	random	**HW**	P_c = 0.9	1.0	0.042	53	24.97	231
F313(D)	**decreasing triangular**	**HW**	p_{dH} = 40	1.0	0.042	53	26.14	248
F302	rectangular	**HW**	p_{dH} = 45	1.0	0.038	56	26.32	293
D369	**decreasing triangular**	EW	i_{max} = 50000	1.0	0.035	53	26.76	398
D28	random	**HW**	T_s = 2	1.0	0.031	53	25.60	390
F277	**decreasing triangular**	**HW**	p_{dH} = 55	1.0	0.029	53	26.13	376
F315(D)	increasing triangular	**HW**	p_{dH} = 40	1.0	0.026	53	25.03	265

Table B-5 - Uncino landslide: the 10 most efficient runs. Benchmark conditions are reported in bold. The only "varied" parameter with respect to the benchmark is reported in the fourth column.

The above 10 most efficient runs were obtained by adopting the benchmark initialization, except for one parameter (cf. Table B-5, fourth column). These runs show all the maximum *fitness*, and a similar *base time* (slightly less than 2 months, coherently with the size of the considered landslide). All the types of initial shape of the kernel and all types of *fitness functions* were employed in such runs. In particular, the *absolute best run* (D309) was obtained by using a "decreasing triangular" *initial shape of kernel*, an *EW fitness function*, and a percentage of mutation of the elements of the kernel equal to 30% (*i.e.*, p_{me} = 0.3).

The main statistics of the 10 most efficient runs are listed in Table B-6. Obtained values underline very similar characteristics of such runs (with modest values for the standard deviations of the considered parameters). Moreover, the *steps* required to first obtain the maximum *fitness* within a given experiment can be reached in very-small computational times (few minutes) on a standard computer. For the same 10 best runs, the *fitness* values obtained in calibration, by employing the 3 types of functions, are listed in Table B-7.

	$\emptyset_n$	Δz_{cr}	t_b	μ_0	*step*
media	1.0	0.040	53.3	26.09	293.7
st. dev.	0.0	0.010	0.95	0.70	74.4
min	1.0	0.026	53	24.97	176.0
max	1.0	0.057	56	27.11	398.0

Table B-6 – Uncino landslide: main statistics of the 10 most efficient runs.

run	$\emptyset_{n(HW)}$	$\emptyset_{n(EW)}$	$\emptyset_{n(ROC)}$
D309	1.0	**1.0**	*0.9997*
F214	1.0	1.0	**1.0**
F269	1.0	**1.0**	1.0
F208	**1.0**	1.0	1.0
F313(D)	**1.0**	1.0	*0.9996*
F302	**1.0**	1.0	*0.9991*
D369	1.0	**1.0**	*0.9991*

D28	**1.0**	1.0	1.0
F277	**1.0**	1.0	*0.9993*
F315(D)	**1.0**	1.0	1.0

Table B-7 – Uncino landslide: fitness obtained in calibration, by using the *best Kernels* of the 10 best runs, employing the 3 types of functions. In bold, values obtained in the run listed in the first column (as also reported in Table B-5, fifth column). In Italics, values close to unity obtained with AUC-ROC.

In Figure B-3, the initialization and output masks related to calibration of run *D309* are shown.

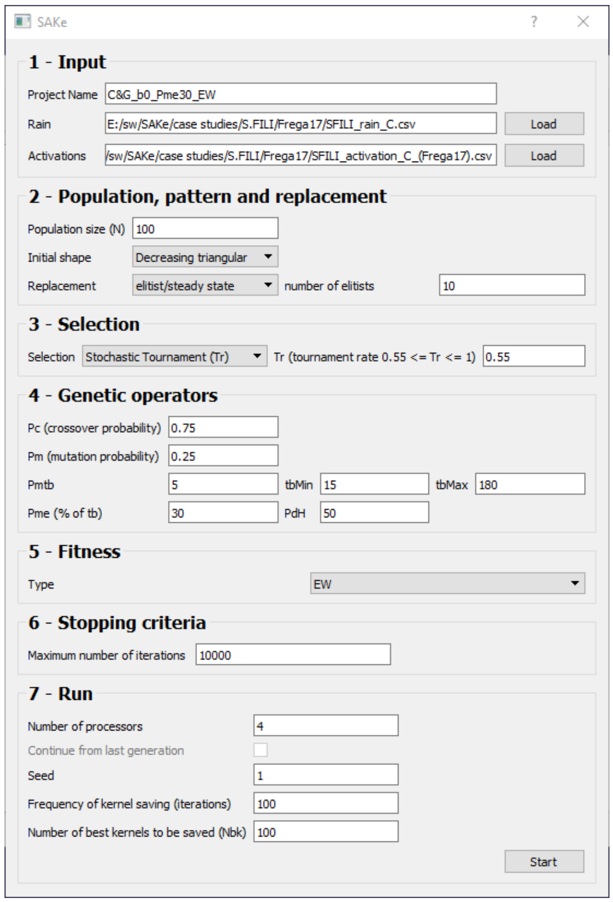


Figure B-3 – Uncino landslide: initialization (top) and output (bottom) masks for calibration of the run *D309*.

For each of the 10 runs listed in Table B-5, a set of 100 *optimal Kernels* (*Q*=100) was employed to synthesize an *average kernel* to be tested in calibration. Again, the *fitness* values obtained by employing the 3 types of functions, are listed in Table B-8.

run	$\emptyset_{n(HW)}$	$\emptyset_{n(EW)}$	$\emptyset_{n(ROC)}$
D309	1.0	1.0	*0.9996*
F214	1.0	1.0	1.0
F269	1.0	1.0	*0.9999*
F208	1.0	1.0	*0.9998*
F313(D)	1.0	1.0	*0.9993*
F302	1.0	1.0	*0.9995*
D369	1.0	1.0	1.0
D28	1.0	1.0	1.0
F277	1.0	1.0	*0.9994*
F315(D)	1.0	1.0	1.0

Table B-8 – Uncino landslide: fitness obtained in calibration, by using the *average synthetic Kernels* of the 10 best runs, by employing the 3 types of functions. In Italics, values close to unity obtained with AUC-ROC.

It should be noticed that the values in Tables B-7 and B-8, obtained by adopting the 3 types of fitness functions, basically show similar maxima (including those evaluated by means of the AUC-ROC method), with differences, at most, to the fourth decimal place. Moreover, different sorting criteria than those mentioned above may also be adopted to select the "best" runs, e.g. by changing the hierarchical order of the considered parameters (*fitness*, Δz_{cr}, t_b, μ_0, *step*).

The *best Kernels*, and the *average synthetic Kernels* of the 10 best runs are shown in Figures B-4 and B-5, respectively. Although the 10 kernels show a fairly complex pattern, they are quite similar to each other. Several "peaks" can be recognised in an antecedent period of 53 days (except for run *F302*, that has t_b=56 days), ascribable by rainfall contribution and related fluctuations of groundwater table. In particular, a major role can be attributed to fluctuations occurred in the following days before landslide occurrence: i) 1-15 days, ii) 22-27 days, iii) 31-34 days, iv) 40-46 days, and v) 50-56 days.

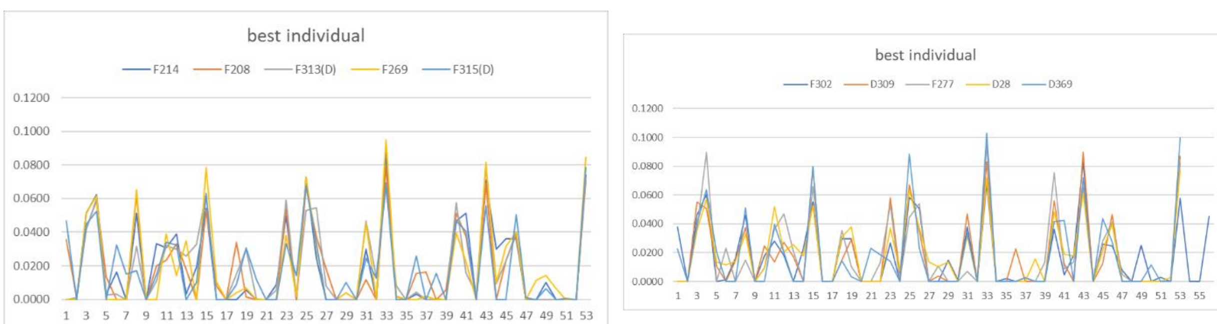


Figure B-4 – Uncino landslide: best kernels of the 10 best runs (for the sake of readability, the set is split in two graphs).

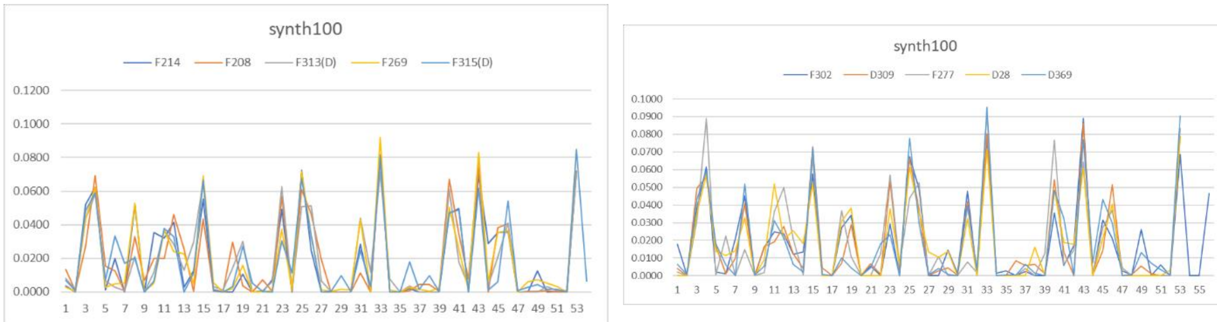


Figure B-5 – Uncino landslide: *average synthetic Kernels* of the 10 best runs (for the sake of readability, the set is split in two graphs).

<u>B.2 – Validation</u>

Starting from the 10 most efficient runs listed in Table B-5, the following validation experiments were performed by considering i) the *best Kernels* of each run (Figure B-4), and ii) the *average synthetic Kernels* of the same best runs (Figure B-5). Note that validation was performed – for all the considered *best* and *average synthetic Kernels* – by considering the entire daily rain series from 01.01.1959 to 31.12.1980, and all the 6 activation dates (cf. Table 2). Obtained fitness results (by employing the 3 types of functions) are listed in Tables B-9 and B-10. – in which, again, similar values are shown.

run	$\emptyset_{n(HW)}$	$\emptyset_{n(EW)}$	$\emptyset_{n(ROC)}$
D309	1.0	1.0	*0.9997*
F214	1.0	1.0	*0.9995*
F269	1.0	1.0	1.0
F208	1.0	1.0	*0.9995*
F313(D)	1.0	1.0	*0.9996*
F302	1.0	1.0	*0.9996*
D369	1.0	1.0	*0.9995*
D28	1.0	1.0	1.0
F277	1.0	1.0	*0.9995*
F315(D)	1.0	1.0	*0.9994*

Table B-9 – Uncino landslide: fitness obtained in validation, by using the *best Kernels* of the 10 best runs, by employing the 3 types of functions. In Italics, values close to unity obtained with AUC-ROC.

run	$\emptyset_{n(HW)}$	$\emptyset_{n(EW)}$	$\emptyset_{n(ROC)}$
D309	1.0	1.0	*0.9998*
F214	1.0	1.0	*0.9995*
F269	1.0	1.0	1.0
F208	1.0	1.0	*0.9994*
F313(D)	1.0	1.0	*0.9994*
F302	1.0	1.0	*0.9997*
D369	1.0	1.0	*0.9995*
D28	1.0	1.0	1.0
F277	1.0	1.0	*0.9995*
F315(D)	1.0	1.0	*0.9998*

Table B-10 – Uncino landslide: fitness obtained in validation, by using the *average synthetic Kernels* of the 10 best runs, by employing the 3 types of functions. In Italics, values close to unity obtained with AUC-ROC.

The initialization and output masks related to validation of run *D309* are shown in Figure B-6.

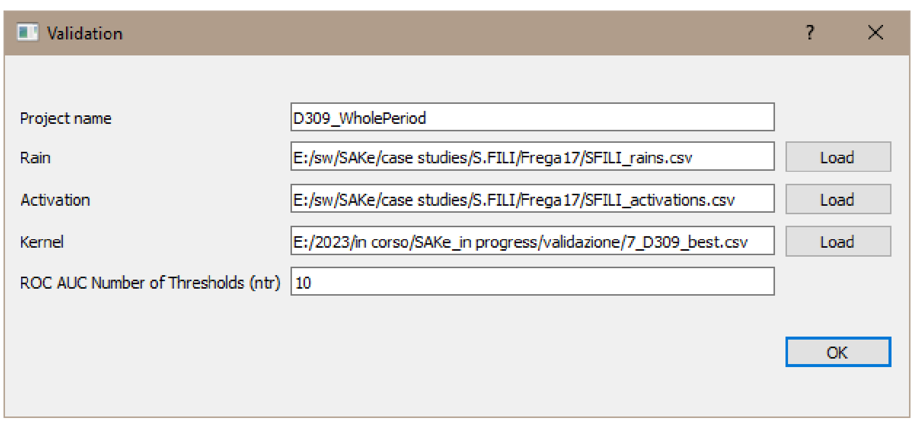


Figure B-6 – Uncino landslide: initialization (on top) and output (at bottom) masks for validation of the *best kernel* of the run *D309*.

B.3 – Regression

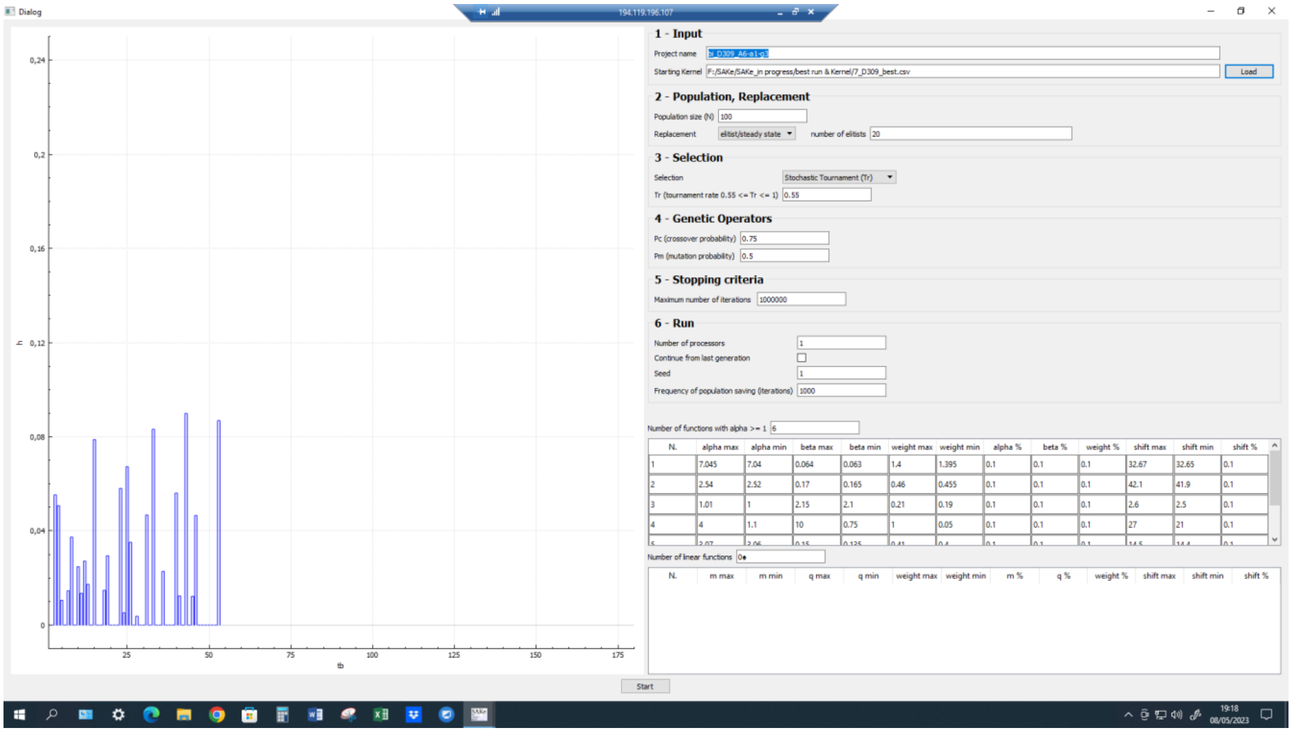
A set of regression experiments were performed, by considering different initialization parameters, *gamma distributions* and *linear functions*. By even considering the *parsimony principle*, the regression performed by considering u_γ = 6 *gamma distributions* and the *best Kernel* of run D309 (cf. Figures B-4 and B-6) resulted among the best ones. Its resulting *goodness of fit* (*NSE* = 62.3799) indicates a quality at the boundary between classes “acceptable” and “very-good/good” (cf. Table 1).

In particular, the tool was initialized as follows: *Population size* (*N*) = 100; *Replacement* = elitist/steady state, with number of elitists (*e*) = 10; *Selection* = Stochastic Tournament, with tournament rate (*Tr*) = 0.55. As concerns the *Genetic Operators*, *Crossover probability* (*Pc*) and *Mutation probability* (*Pm*) were set to 0.75 and 0.5, resp. In addition, the following *operational parameters* were adopted: *maximum number of iterations* = 1,000,000; *number of processors* = 1; *seed* = 1; *frequency of population saving* = 1,000. For each *gamma distribution* $f_k(t)$, the ranges and percentages of mutation for α, β, w_k were initialized, together with ranges and percentage of shift (Δt_k), as shown in Table B-11, based on a preliminary set of trial-and-error experiments.

N.	1	2	3	4	5	6
α_{max}	7.045	2.54	1.01	4	3.07	7.18
α_{min}	7.04	2.52	1.0	1.1	3.06	7.17
β_{max}	0.064	0.17	2.15	10.0	0.15	0.4
β_{min}	0.063	0.165	2.1	0.75	0.135	0.39
$w_{k_{max}}$	1.4	0.46	0.21	1.0	0.41	1.212
$w_{k_{min}}$	1.395	0.455	0.19	0.05	0.4	1.21
α %	0.1	0.1	0.1	0.1	0.1	0.1
β %	0.1	0.1	0.1	0.1	0.1	0.1
w_k%	0.1	0.1	0.1	0.1	0.1	0.1
$\Delta t_{k_{max}}$	32.67	42.1	2.6	27	14.5	52.5
$\Delta t_{k_{min}}$	32.65	41.9	2.5	21	14.4	51.5
Δt_k%	0.1	0.1	0.1	0.1	0.1	0.1

Table B-11 – Uncino landslide: values of adopted regression parameters for 6 *gamma distributions*.

In Figure B-7, the initialization and output masks for the above-described regression are shown. The resulting values of the parameters defining *H(t)* are listed in Table B-12. The regression results represent an analytical approximation (by means of 6 *gamma distributions*) of the discrete kernel obtained in calibration (as discussed in Appendix B.1). By examining the obtained function *H(t)*, n. 6 peaks characterize its pattern, thus underlining that a number of short rainfall episodes are required to trigger the considered landslide. By the way, the decreasing role of antecedent rains is testified by a couple of descending branches lasting 3-4 weeks – in some ways, analogous to the depletion curve of an underground aquifer.



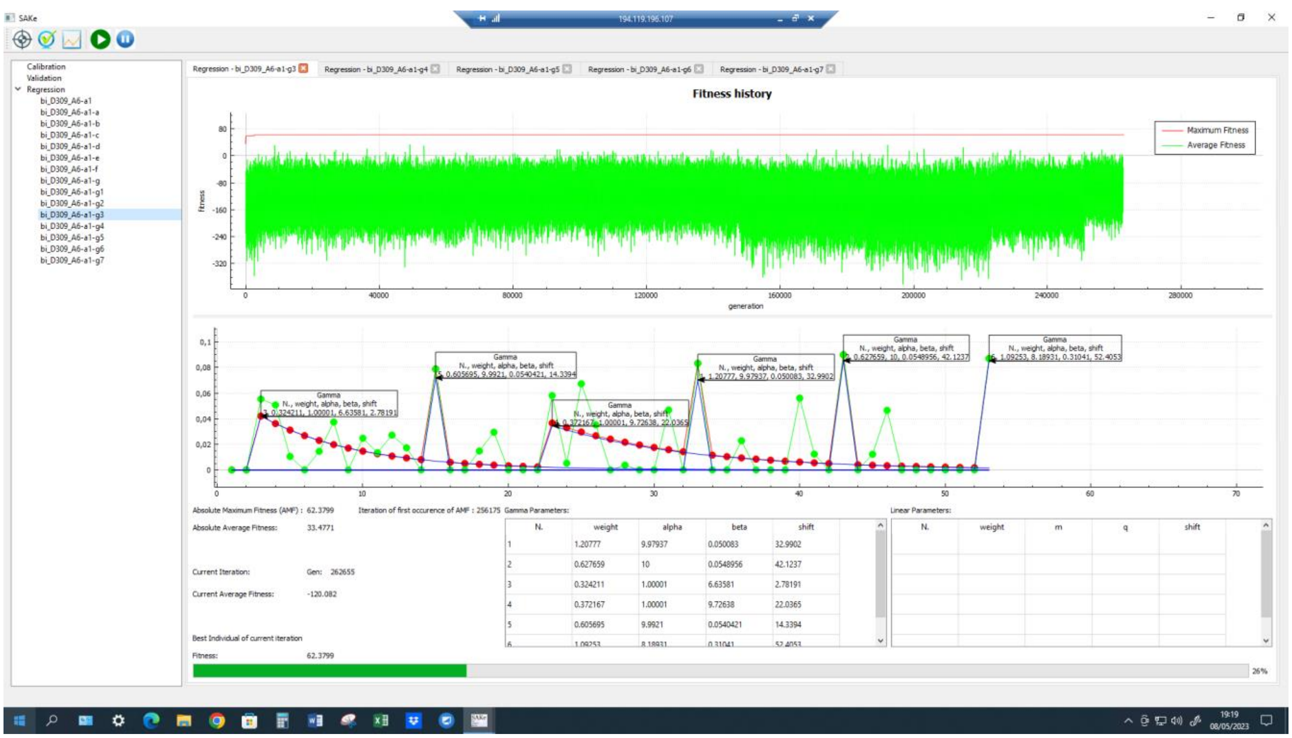


Figure B-7 – Uncino landslide: initialization (on top) and output (at bottom) masks for regression of the *best Kernel* of run *D309*.

k	w_k	α	β	Δt_k
1	1.20777	9.97937	0.050083	32.9902
2	0.627659	10	0.0548956	42.1237
3	0.324211	10.00001	6.63581	2.78191
4	0.372167	1.00001	9.72638	22.0365
5	0.605695	9.9921	0.0540421	14.3394
6	1.09253	8.18931	0.31041	52.4053

Table B-12 – Uncino landslide: values of regression parameters defining *H(t)*, as obtained for the *best Kernel* of run *D309*, using 6 *gamma distributions*.