GASAKe: forecasting landslide activations by a Genetic-Algorithms based hydrological model

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ABSTRACT

GASAKe is a new hydrological model aimed at forecasting the triggering of landslides. The model is based on Genetic Algorithms and allows to obtain thresholds for the prediction of slope failures using dates of landslide activations and rainfall series. It can be applied to either single landslides or set of similar slope movements in a homogeneous environment.

Calibration of the model provides families of optimal, discretized solutions (kernels) that maximize the fitness function. Starting from the kernels, the corresponding mobility functions (i.e., the predictive tools) can be obtained through convolution with the rain series. The base time of the kernel is related to the magnitude of the considered slope movement, as well as to the hydro-geological complexity of the site. Generally, shorter base times are expected for shallow slope instabilities compared to larger-scale phenomena. Once validated, the model can be applied to estimate the timing of future landslide activations in the same study area, by employing measured or forecasted rainfall series.

Examples of application of GASAKe to a medium-size slope movement (the Uncino landslide at San Fili, in Calabria, Southern Italy) and to a set of shallow landslides (in the Sorrento Peninsula, Campania, Southern Italy) are discussed. In both cases, a successful calibration of the model has been achieved, despite unavoidable uncertainties concerning the dates of occurrence of the slope movements. In particular, for the Sorrento Peninsula case, a fitness of 0.81 has been achieved by calibrating the model against 10 dates of landslide activation; in the Uncino case, a fitness of 1 (i.e., neither missing nor false alarms) has been achieved using 5 activations. As for temporal validation, the experiments performed by considering further dates of activation have also proved satisfactory.

In view of early-warning applications for civil protection, the capability of the model to simulate the occurrences of the Uncino landslide has been tested by means of a progressive, self-adaptive procedure. Finally, a sensitivity analysis has been performed by taking into account the main parameters of the model.

The obtained results are quite promising, given the high performance of the model against different types of slope instabilities characterized by several historical activations. Nevertheless, further refinements are still needed for application to landslide risk mitigation within early-warning and decision-support systems.

Key words: hydrological model, rainfall threshold, landslide triggering, genetic algorithm
1 INTRODUCTION

A nationwide investigation, carried out by the National Geological Survey, identified approximately $5 \times 10^5$ slope movements in Italy, with an average of 1.6 failures per square kilometre (Trigila, 2007). According to other investigations, this figure would rather be a low estimate (cf. Servizio Geologico, Sismico dei Suoli, 1999; Guzzetti et al., 2008). In the period 1950–2009, at least 6349 persons were killed, went missing, or were injured by landslides, with an average of 16 harmful events per year, thus confirming the notable risk posed to population (Guzzetti, 2000; Salvati et al., 2010).

Petley (2008) estimated that about 90% of worldwide casualties can be attributed to landslides triggered by rainfall. With reference to the Italian territory, about 70% of landslides result to be triggered by rainfall (cf. CNR-GNDCl AVI Project, Alfieri et al., 2012). Slope instability conditions are in fact influenced by rainfall that, infiltrating into the slopes, cause temporary changes in groundwater dynamics (Van Asch et al., 1999). The combination of infiltration and runoff may cause different types of mass-movements (either slope failure or erosion processes) depending on the intensity and duration of the rainfall and the values of soil suction (Cuomo and Della Sala, 2013). Concentration of water deriving from either contemporary or antecedent storms at specific sites plays a major role in triggering landslides – as testified by slope instabilities that commonly follow the heaviest phases of rainfall events.

To model the relationships between rainfall and landslide occurrence, two distinct approaches are generally adopted in literature. The first, named “complete” or “physically-based”, attempts to determine the influence of rainfall on slope stability by modelling its effects in terms of overland flow, groundwater infiltration, pore pressure and related balance of shear stress and resistance (cf. e.g., Montgomery and Dietrich, 1994; Wilson and Wieczorek, 1995; Crosta, 1998; Terlien, 1998; Crosta et al., 2003; Pisani et al., 2010). With regard to this latter purpose, numerical models are employed, and a notable (and expensive) amount of detailed data is commonly required to define the geological scheme of the slope in litho-structural, hydrogeological, morphologic and geotechnical terms. The second approach (adopted in the present study), named “empirical” or “hydrological” (Cascini and Versace, 1988), is based on a statistical-probabilistic analysis of rainfall series and of dates of occurrence of slope movements (see, among the others, Campbell, 1975; Caine, 1980; UNDRO, 1991; Sirangelo and Versace, 1996; Guzzetti et al., 2007; 2008, Brunetti et al. 2010, Gariano et al., 2015). In literature, methodological examples generally focus on thresholds obtained for i) single phenomena or ii) given types of landslides within a homogeneous geo-environmental setting (cf. e.g., Jakob and Weatherly, 2003).

In this study, the hydrological model $G^A S A K e$ (i.e., the Genetic-Algorithms based release of the model Self Adaptive Kernel), developed to forecast the triggering of slope movements, is described. The model can be applied to either single landslides or to a set of similar phenomena within a homogeneous study area. Model calibration is performed by means of Genetic Algorithms: in this way, a family of optimal, discretized kernels can iteratively be obtained from initial tentative solutions. In a different release of the model ($C^M S A K e$ – i.e., Cluster model SAKe) the calibration is instead performed through an iterative procedure (Terranova et al., 2013).

Examples of application of the model to a medium-size landslide (the Uncino landslide at San Fili) and to shallow slope movements in the Sorrento Peninsula are discussed in the following sections. Temporal validation is discussed for both cases, in view of early-warning applications of $G^A S A K e$ for Civil Protection purposes. Moreover, a progressive, self-adaptive procedure of calibration and validation is discussed, by considering the Uncino case study, to verify changes in fitness,
predictive ability and base time when an increasing number of dates of activation is employed.
Finally, the results of preliminary, parametric analyses are presented, aimed at investigating the role
of the main parameters of the model.

2 BACKGROUND
Physical systems evolve in time due to their own inner dynamics and/or as a consequence of
external causes. Suitable observational tools can be employed to monitor their evolution, and
arranged to promptly send reports or warnings to authorities of civil protection to support the
management of emergencies (Cauvin et al., 1998; for applications to landslides, cf. also Keefer et
al., 1987; Iovine et al., 2009; Capparelli and Versace, 2011; Pradhan and Buchroithner, 2012).
In the case of complex systems (e.g., nuclear power stations, telecommunication networks, etc.),
many parameters, in part interdependent, have to be monitored. Missing an automated phase of
analysis and proper filtering, a great number of reports may be delivered by the monitoring
apparatus in few seconds. At this purpose, the concepts of threshold (Carter, 2010), event and
warning must therefore be suitably defined.
Regarding slope movements, the notions of threshold and warning have long been investigated. In
particular, a threshold constitutes a condition - generally expressed in quantitative terms or through
a mathematical law - whose occurrence implies a change of state (White et al., 1996). According to
the ALARM study group (Cauvin et al., 1998), an event is i) a portion of information extracted
from either continuous or discrete signals (i.e., a significant variation), transmitted by a component
of the monitoring network; or ii) a set of data concerning the considered context (e.g., restorations,
actions, observations). According to such definition, an event must be instantaneous and dated. As
for warning, its definition derives from that of event: it is a discrete indicator aimed at triggering a
human or an automated reaction. The warning can be classified into distinct levels (e.g., in terms of
security) or by type (e.g., related to a distinct component of the dynamic system under
consideration), to be transmitted by the monitoring system.
In complex systems, causal factors responsible for emergency conditions may be difficult to
identify. Therefore, warnings may be issued according to pre-fixed thresholds related to suitable
physical properties of the system. In these cases, the timing of data sampling of the monitoring
instruments should be progressively adapted to the evolution of the phenomenon. A further issue
corns the chances of missing and false alarms, as well as the camouflage of an alarm among
simultaneous others.
In physical terms, slope instability can occur when the shear strength gets lower than a given
threshold (Terzaghi, 1962). Rain infiltration may temporarily change the dynamics of groundwater
(Van Asch et al., 1999): due to an increase in pore water pressure, the effective shear strength of the
material decreases, and a slope movement can be triggered. Groundwater may reach a given
location within the slope by different paths. The main natural mechanisms include: i) surface flow,
strongly influenced by morphology; ii) direct infiltration from the surface; iii) flow within the soil
mantle (throughflow) from upslope and sideslopes; iv) seepage from the bedrock toward the
overlying colluvium. The length of the different paths may be quite different, and characterized by
distinct velocities: as a consequence, aliquots of the same rainfall event may reach a given site at
different times, variously combining with other groundwater amounts (Ellen, 1988).
To apply a hydrological approach, empirical relations have to be determined by means of thresholds
to distinguish among conditions which likely correspond to landslide occurrence or not. To this
aim, different hydrological parameters can be selected (Guzzetti et al., 2007; 2008 and
http://rainfallthresholds.irpi.cnr.it/): the cumulative rain recorded in a given temporal window (hours/days/months) before landslide activation; the average rain intensity in the same temporal window; rains normalized to reference values (e.g., annual averages). Simplified hydrological balances can also be adopted in empirical approaches, by considering losses of aliquots of rains by run-off, evapo-transpiration, etc.

As concerns superficial landslides, triggering thresholds can be derived from relations between the “triggering” rain (daily, hourly or shorter), corresponding to the onset of the slope movement, and the rain cumulated over an “antecedent period” (usually, few days to two weeks before landslide activation) (e.g., Campbell, 1975; Cannon and Ellen, 1985; Wieczorek, 1987; Terlien, 1996; Crosta, 1998; Zêzere and Rodrigues, 2002). In other cases, thresholds refer to relations between rain intensity, \( I \), and duration, \( D \) (e.g., Brunetti et al., 2010, Berti et al., 2012, Peres and Cancelliere, 2014). In some studies, antecedent rains are also considered, allowing to obtain better results (e.g., Campbell, 1975). Larger amounts of antecedent rain should allow slope movements to be activated by less severe triggering storms. In general, a direct relationship between antecedent rain and landslide dimension can be observed (Cascini and Versace, 1986); though, in some peculiar conditions (e.g., Hong Kong case studies, caused by suction reduction - Brand et al., 1984) this is not the case, and the role of antecedent rains looks less important. In addition, as underlined by Cuomo and Della Sala (2013), time to runoff, time to failure and runoff rates strongly depend on soil water characteristic curves, soil initial conditions, rainfall intensity and slope angle in unsaturated shallow deposits. Moreover, soil mechanical parameters affect the time to failure, which can result either shorter or longer than time to runoff.

Due to physical and economic issues, difficulties in hydrological modelling of landslides generally increase when dealing with deeper and larger phenomena (Cascini and Versace, 1986). In such cases, landslide activation depends on the dynamics of deeper groundwater bodies. By the way, it is not by chance that most studies do refer to small and superficial slope movements. Large landslides usually show complex relationships with rains, as different groundwater aliquots may combine and reach the site of triggering. Depending on type (cf. dimension, material, kinematics, etc.), different hydrological mechanisms should be considered, thus limiting the possibility of generalization of the thresholds (Dikau and Schrott, 1999; Corominas, 2001; Marques et al., 2008). Again, the mobilization of deeper phenomena commonly requires greater rainfall amounts, spanned over longer periods, with respect to shallow landslides (Aleotti, 2004; Terranova et al., 2004; Guzzetti et al., 2007; 2008;). In these cases, rain durations responsible for landslide activations commonly range from ca. 30 days to several months, even beyond a single rainy season (Brunsden, 1984; Van Asch et al., 1999; Gullà et al., 2004; Trigo et al., 2005).

To analyse the triggering conditions of slope movements – either shallow or deep-seated – a threshold-based modelling approach can be employed. Empirical thresholds (e.g., Aleotti, 2004; Wieczorek and Glade, 2005; Terranova et al., 2004; Vennari et al., 2014) can be expressed in terms of curves, delimiting the portion of the Cartesian plane which contains “all and only” the hydrological conditions related to known activations (cf. e.g., the \( I-D \) chart proposed by Caine, 1980). A further improvement to this approach can be obtained by considering hydrological conditions not related to landslide activations (Crozier, 1997; Sengupta et al., 2010; Gariano et al., 2015). In general, no changes of state are assumed to occur below the threshold \( z_t \), while they do happen above it. Alternatively, a range of conditions can be defined (Crozier, 1997), delimited by:

- a lower threshold \( z_{low} \), below which changes of state do never occur, and
- an upper threshold \( z_{upp} \), above which changes always happen.

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For values between \( z_{\text{upp}} \) and \( z_{\text{low}} \), the probability that the state changes can be defined, essentially depending on (i) the incompleteness of knowledge on the physical process under investigation, and (ii) the incapacity of the model to fully replicate the behaviour of the same process. In probabilistic terms:

\[
P(E_t) = 0 \text{ for } z(t) < z_{\text{low}}
\]
\[
P(E_t) = 1 \text{ for } z(t) > z_{\text{upp}}
\]
\[
P(E_t) = G[z(t)] \text{ for } z_{\text{low}} \leq z(t) \leq z_{\text{upp}}
\]

in which: \( P \) is the probability of occurrence (1=success, 0=unsuccess); \( E_t \) is a process (succession of events) whose state changes with time \( t \); \( z(t) \) is the value assumed, at time \( t \), by the variable that determines the change of state; \( z_{\text{low}} \) and \( z_{\text{upp}} \) are the minimum and maximum thresholds, respectively; \( G[z(t)] \) is a probability function, monotonically increasing with \( t \) in the range \([0,1] \).

In hydrological models, to express the influence of rainfall on runoff and groundwater dynamics, a “kernel” (also named “filter function”) can be employed, usually defined in terms of simple, continuous analytical function (Chow et al., 1988). In such a way, suitable weights can be assigned to the precipitations occurred in the last hours/days before a given geo-hydrological process (e.g., discharge, measured at a generic river cross section; landslide activation), as well as to earlier rains recorded weeks/months before. The mostly employed types of kernels are Beta, Gamma, Nash, negative exponential distribution. Furthermore, the “base time” (\( t_b \)) expresses a sort of memory with respect to rainfall: in classic rainfall-runoff modelling, \( t_b \) defines the time of concentration, while in slope stability analyses it represents the time interval, measured backward from landslide activation, during which rainfall is deemed to effectively affect groundwater dynamics, and contributes to destabilization.

To modelling slope stability, both the shape and the base time of the kernel must be properly selected depending on type and dimension of the investigated phenomena, as well as geo-structural and hydrogeological characteristics. Unfortunately, in several real cases, the above-mentioned analytical functions may fail in properly capturing the complexity of groundwater dynamics, as well as the related landslide activations. In this respect, the adoption of discretized kernels, automatically calibrated through iterative computational techniques, may offer effective solutions.

3 THE MODEL \( G^4 S A K e \)

\( G^4 S A K e \) is an empirical-hydrological model for predicting the activation of slope movements of different types. It is based on a classic threshold scheme: the exceedance of the threshold determines a change of state, i.e. the triggering of the landslide. The scheme is inspired from the \( F L a I R \) model (Forecasting Landslides Induced by Rainfall), proposed by Sirangelo and Versace (1996): through changes of state in time, the variable \( z(t) \) assumes the meaning of “mobility function”. In other terms, the values of \( z(t) \) depend on the amount of rain stored in the aquifer.

In hydrology, rainfall-runoff modelling is commonly performed by adopting a linear, steady scheme (Chow et al., 1988). Such approach implies that the transformation of rainfall in runoff can be described by an integral of convolution between a unitary impulsive response of the basin – the kernel, \( h(t) \) – and the rainfall, \( p(t) \).

The kernel (filter function) represents the unitary volume influx in an infinitesimal period, and is defined as:

\[
\int_{0}^{\infty} h(t) dt = 1
\]
in which $h(t) = h(-t)$, $h(t) \geq 0$, $\forall t$.

In practical applications, the lower bound ($t=0$) corresponds to the beginning of the flood-wave rising, and the kernel assumes a finite duration ($t_b$). The integral of convolution is therefore expressed as:

$$z(t) = \int_{0}^{t_b} h(t - \tau) p(\tau) d\tau = \int_{0}^{t_b} h(\tau) p(t - \tau) d\tau$$

(3)

in which $z(t)$ represents the discharge at the time $t$. For a specific case study, the kernel can be determined by means of calibration procedures, by relating discharge measurements to rains.

In discretized terms, the elements of the kernel are characterized by width $\Delta t$ and height $h_i$, and equation (3) can be written as:

$$z_u = \sum_{i=1}^{u} h_i \cdot p_{u-i+1} \cdot \Delta t$$

(4)

Sirangelo and Versace (1996) proved that the same approach may turn out promising also in slope-stability modelling. Capparelli and Versace (2011) stressed that the I-D chart of Caine (1980) corresponds to a kernel defined by a power function $h(t) = a t^b$, with $b<0$. Exporting the well-established knowledge of rainfall-runoff modelling (usually based on many measurements) to rainfall-landslide modelling is not trivial, due to scarcity of adequate information for proper calibration. Only few dates of activation are, in fact, commonly available in rainfall-landslide modelling (often with unsatisfactory details on location and phenomena), and the values of $z(t)$ are unknown. From a mathematical point of view, such a problem can be handled by assuming that the timing of the maxima of $z(t)$ corresponds to the dates of landslide activation. When studying the triggering conditions of landslides, calibration can be therefore performed by maximizing the mobility function in correspondence to the dates of activation.

Scarcity of information inevitably reflects on the resulting kernel, whose shape may turn out highly indeterminate: different functions, or different parameters of the same function, can in fact maximize $z(t)$ in correspondence to the dates of mobilization. Model optimization – and its reliable utilization for early-warning purposes – can turn out an awkward issue.

In this work, an innovative modelling approach – based on discretized kernels, automatically calibrated through iterative computational techniques – is proposed, which may help in facing the above-cited difficulties. For modelling purposes, the rainfall series and a coherent set of dates of landslide occurrence – either related to a given slope movement, or to a set of landslides of the same type in a homogeneous geo-environmental zone – must be given as input.

Unfortunately, when dealing with the timing of occurrence, historical notices may refer either to portions of the considered phenomena or to entire landslide bodies. Therefore, dates should be properly selected to consider only consistent cases. Moreover, dates of activation are usually known with only a broad approximation: with respect to the reports, the actual timing of occurrence may be located backward (documents may assign a later date) or forward (in case of later, more relevant movements). For modelling purposes, it is then useful to specify a temporal window, lasting from an initial ($d_{from}$) to a final date ($d_{to}$), containing the presumable timing of occurrence.

Rainfall series are commonly reconstructed from data recorded at rain gauges located within a reasonable proximity of the study site. The temporal window of the hydrological analysis is defined by the intersection of $i$) the period of observation of the rains and $ii$) the period delimited by the ancientmost and the recentmost dates of activation of the landslide. A potential source of
uncertainty lies in the fact that, occasionally, the recorded rainfall amounts notably differ from those actually experienced at landslide location. Furthermore, landslide triggering may also be due to other causes (e.g., human activity, earthquakes): a thorough preliminary analysis has always to be performed to verify the significance of rainfall preceding landslide activation, to detecting cases not to be considered in the hydrological study.

In the model, rains older than $t_b$ are neglected. Suitable maximum and minimum values ($t_{b,\text{max}}$ and $t_{b,\text{min}}$) have to be initialized to allow the model to determine optimal values. Commonly, $t_b$ ranging from few hours to some weeks are suggested for shallow landslides, while greater values (up to several months) sound suitable for deep-seated phenomena.

Based on the geological knowledge of the phenomenon under investigation, the initial shape of the kernel can be assumed among a set of basic types. Among these, i) a “rectangular” shape can be adopted if older precipitations have the same weight of more recent rains; ii) a “decreasing triangular”, if older precipitations have a progressively smaller weight than more recent rains; iii) “increasing triangular”, if older precipitations have a progressively greater weight than more recent rains. A casual shape or any other function can also be implemented in the model (e.g., Beta, Gamma, Nash, Negative exponential distribution).

3.1 Model Calibration

In $^{GASAKe}$, model calibration is performed against real case studies through Genetic Algorithms (GAs). These latter are general-purpose, iterative search algorithms inspired by natural selection and genetics (Holland, 1975). Since 1970’s, GAs have been applied to several fields of research, from applied mathematics (Poon and Sparks, 1992), to evolution of learning (Hinton and Nowlan, 1987), evolutionary robotics (Nolfi and Marocco, 2001), and debris-flow modelling (Iovine et al., 2005; D’Ambrosio et al., 2006). GAs simulate the evolution of a population of candidate solutions to a given problem by favouring the reproduction of the best individuals. The candidate solutions are codified by genotypes, typically using strings, whose elements are called genes.

GAs explore the solution space, defined as the set of possible values of the genes. At the beginning of a given optimization experiment, the members of the initial population of genotypes (in this study, the kernels) are usually generated at random. The performance of each solution, in terms of phenotype (i.e., the mobility function), is evaluated by applying a suitable fitness function, so determining its “adaptability”, i.e. the measure of its goodness in resolving the problem.

The sequence of random genetic operators selection, crossover and mutation, constrained by prefixed probabilities, constitutes a single GA-iteration that generates a new population of candidate solutions. At each iteration, best individuals are in fact chosen by applying the selection operator. To form a new population of offspring, crossover is employed by combining parents’ genes. Mutation is successively applied to each gene, by randomly changing its value within the allowed range. Thanks to the GA approach, better individuals (i.e., those characterized by higher fitness values) can be obtained over time. In fact, according to individual probabilities of selection, any change that increases the fitness tends to be preserved over GA iterations (Holland, 1975). For further details on GAs, cf. Goldberg (1989) and Mitchell (1996).

In the present study, a steady-state and elitist GA (cf. De Jong, 1975) was employed to obtain the family of optimal kernels that maximize the mobility function in correspondence to known dates of landslide activations. The procedure employed for calibration of $^{GASAKe}$ is schematized in Figure 1. At the beginning of an optimization experiment, the initial population of $N$ kernels is generated at random, and the fitness of the related mobility functions is evaluated (cf. below). In order to evolve
the initial population of candidate solutions, and to progressively obtain better solutions, a total
number of GA-iterations follows.

At each iteration of the GA, the operators selection, crossover and mutation are applied as follows
(Fig. 2):

- **selection**
  1. $n_e$ “elitist” individuals are merely copied in a “mating pool” from the previous generation, by
     choosing the best ones;
  2. the remaining $N-n_e$ candidate solutions are chosen by applying the “tournament without
     replacement” selection operator. More in detail, a series of tournaments are performed by
     selecting two individuals at random from the previous generation: the winner (i.e., the one
     characterized by the highest fitness) is copied into the mating pool, according to a prefixed
     surviving probability ($p_s$), which is set greater for the fittest individual. Note that, when
     choosing the $N-n_e$ candidate solutions, a given individual cannot be selected more than once.

- **crossover**
  After the mating pool is filled with $N$ individuals, the crossover operator is applied, according to
  a prefixed probability ($p_c$):
  1. two parent individuals are chosen from the mating pool at random;
  2. a cutting point (crossover point) is then selected at random in the range \([t_{b-min}, t_{b-max}]\);
  3. the obtained portions of parents’ strings are exchanged, thus mixing the genetic information
     and resulting in two children (Fig. 3).

  When the crossover is not applied, the two parents are merely copied into $P_{new}$.

- **mutation**
  Based on a prefixed probability ($p_m$), a random number of elements of the kernel ($p_{mev}$, expressed
  as a percentage of $t_b$) is mutated, by adding to each element an amount $dh$ that is randomly
  obtained in the range \([p_{mh1}, p_{mh2}]\), as a function of the maximum value of the kernel ($h_{max}$). Then
  $dh$ ranges from $dh_1$ to $dh_2$:

  \[
  dh_1 = p_{mh1} \cdot h_{max} \\
  dh_2 = p_{mh2} \cdot h_{max} 
  \]

  Furthermore, the base time is also mutated (increased or decreased) within the bounds \([t_{b-min}, t_{b-
  max}]\), according to a random factor $dt_b$ selected in the range \([1/p_{mtb}, p_{mtb}]\) (Fig. 4).

  Children obtained by either crossover or mutation must be normalized before being included in the
  population $P_{new}$, by properly scaling the elements of the kernels to ensure validity of equation 2.

  During calibration, the shape of the kernel and its $t_b$ are iteratively refined. Note that the shape is not
  subject to any constraint, while $t_b$ is allowed to vary in the range \([t_{b-min}, t_{b-max}]\). The fitness is
  computed for each examined mobility function, and new populations of kernels are generated as
  described above.

  As for the fitness function, in $G^4SAKe$ it is defined as follows:
  1. the $L$ available dates of landslide activation – as derived from the historical analyses – are
     arranged in a vector $S = \{S_1, S_2, \ldots, S_i, \ldots, S_L\}$;
  2. the vector of the relative maxima of the mobility function, $Z = \{z_1, z_2, \ldots, z_j, \ldots, z_M\}$, is sorted
     in decreasing order ($M = \text{number of relative maxima}$);
  3. the vector of the partial fitness is $\phi = \{\phi_1, \phi_2, \ldots, \phi_i, \ldots, \phi_L\}$, where $\phi_i = k^{-1}$ depends on the rank $k$
     of the relative maxima of $z_j$ that coincide with known dates of activation, $S_i$. In case $S_i$ does not
     correspond to any relative maximum, it is $\phi_i = 0$. 

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With reference to a given kernel, the resulting fitness is expressed by $\Phi_u = \sum_{i=1}^{L} \varphi_i$. To generalize the results for an easier comparison with other study cases, a normalized fitness index is adopted, $\Phi = \Phi_u / \Phi_{\text{max}}$, defined in the range $[0,1]$, being $\Phi_{\text{max}} = \sum_{i=1}^{L} 1 / i$.

For instance, if two dates of activation are available and both are well captured by the mobility function (i.e., they correspond to the highest peaks), the obtained fitness is $\Phi_u = 1 + \frac{1}{2} = 1.5$. On the other hand, in case only one of the dates is captured and the remaining one ranks fifth, $\Phi_u = 1 + \frac{1}{5} = 1.2$.

Thanks to the above procedure, a family of “optimal kernels” which maximizes the fitness can be determined. The mobility function is, in fact, forced toward a shape characterized by relative maxima ($z_i$) coinciding with the dates of landslide occurrence ($S_i$). An optimal solution leads to a mobility function having the highest peaks in correspondence to such dates; further peaks may also be present, characterized by lower values. Nevertheless, kernel solutions generally determine mobility functions whose highest peaks only partly match with the dates of landslide occurrence (i.e., some dates may neither correspond to the highest peaks nor to any peak at all).

To select the most suitable kernel from a given family of optimal ones, let’s define:

- $z_{j\text{-min}}$ as the lowest of the peaks of the mobility function in correspondence to one of the dates of activation ($S_j$);
- $z_{cr}$ as the “critical threshold”, i.e. the highest peak of the mobility function just below $z_{j\text{-min}}$;
- the “safety margin”, $\Delta z_{cr} = (z_{j\text{-min}} - z_{cr}) / z_{j\text{-min}}$.

When applying the fitness function to evaluate a given kernel, either incompleteness or low accuracy of input data may lead to “false alarms” – i.e., peaks of the mobility function ($z_i$) which are greater than the threshold $z_{cr}$, but do not correspond to any of the known dates of activation. Such alarms can actually be of two different types: 1) “untrue false”, due to an informative gap in the archive (i.e., correct prediction); 2) “true false”, in case of real misprediction of the model. On such cases, further historical investigations may help to discriminating between the mentioned types of false alarms.

Also depending on the specific purpose of the analysis, the most suitable kernel can therefore be selected by one or more of the following criteria: i) the greatest $\Delta z_{cr}$; ii) the shortest $h_t$; iii) the smallest $\mu_0 = \sum_{i=t_b}^{t_0} (i - 0.5) h_i \Delta t$, i.e. the first-order momentum of the kernel with respect to the vertical axis. The first criterion allows for the activation of early-warning procedures with greatest advance; the remaining ones (to be employed when $\Delta z_{cr}$ is too small) generally correspond to more impulsive responses to rainfall.

Differently from what usually experienced in rainfall-runoff models, GASAKE therefore provide multiple equivalent solutions – i.e., a number of optimal kernels with same fitness, $\Phi_u$, despite different shapes. This may depend on the limited number of available dates of activations, and on other noises in input data (e.g., rain gauges located too far from the site of landslide activation; inaccurate information on dates of activation or on the phenomenon). The adoption of synthetic kernels – e.g., obtained by averaging a suitable set of optimal kernels – permits to synthetize the family of results for successive practical applications: in this work, the best 100 kernels obtained for each case study were in fact utilized to synthetize “average kernels” (see below) to be employed for validation purposes.

4 CASE STUDIES
The case studies considered in this paper are: i) a set of shallow landslides in the Sorrento Peninsula between Gragnano and Castellammare di Stabia (Campania, Southern Italy); and ii) the Uncino landslide at San Filì (Calabria, Southern Italy).

Note that, as the numbers of known historical activations in the study areas were adequate, some dates could be excluded from calibration, and were successively employed for validation purposes. In particular, the recentmost dates of landslide activation (cf. Tables 1 and 2) were employed to validate the average kernels (these latter obtained from the families of optimal solutions defined through calibration). The procedure employed for validation is schematized in Figure 5.

4.1 Shallow landslides in the Sorrento Peninsula - Campania

The Sorrento Peninsula is located in western Campania, Southern Italy (Fig. 6). In the area, Mesozoic limestone mainly crop out, covered by Miocene flysch, Pleistocene volcanic deposits (pyroclastic fall, ignimbrite), and Pleistocene detrital-alluvional deposits (Di Crescenzo and Santo, 1999). The carbonate bedrock constitutes a monocline, gently dipping towards WNW, mantled by sedimentary and volcanoclastic deposits, with thickness ranging from few decimetres to tens of meters.

Rainfall-induced shallow landslides are widespread in the pyroclastic soils covering the slopes of the study area. Among the various factors affecting the spatial distribution and the type of slope instabilities, Cascini et al. (2014) pointed out that both the rainfall conditions and the consequent seasonal variations of soil suction play a significant role. In particular, when suction is low and frontal rainfall occurs (from November to May), first time shallow landslides are triggered; when suction is high or very high and convective or hurricane-type rainfall occurs (from June to October), mostly erosion phenomena occur, often turning into hyperconcentrated flows.

The study area is characterized by hot, dry summers and moderately cold and rainy winters. Consequently, its climate can be classified as Mediterranean (Csa in the Köppen-Geiger's classification). In particular, the mean annual temperature ranges from 8-9°C, at the highest elevations of M. Faito and M. Cerreto, to 17-18°C along coasts and valleys. Average annual rainfall varies from 900 mm west of Sorrento to 1500 mm at M. Faito; moving inland to the East, it reaches 1600 mm at M. Cerreto and 1700 mm at the Chiunzi pass (Ducci and Tranfaglia, 2005). On average, annual totals are concentrated in about 95 rainy days. During the driest six months (from April to September), only 30% of the annual rainfall is recorded in about 30 rainy days. During the three wettest months (November, October, and December), a similar amount is recorded in about 34 rainy days (Servizio Idrografico, 1948-1999). In the area, convective rainstorms may occur, characterized by a very high intensity, at the beginning of the rainy season (from September to October). In Autumn-Winter, either high intensity or long duration rainfall are usually recorded, while uniformly distributed rains generally occur in Spring (Fiorillo and Wilson, 2004). As for annual maxima of daily rainfall recorded at the sea level, the Amalfi coast (southern border of the Sorrento Peninsula) is characterized by smaller values (59 mm) of average annual maxima of daily rainfall than the Sorrento coast (86 mm), on the northern border. Such difference seems to persist even at higher elevations (up to 1000 m a.s.l.), with 84 mm vs. 116 mm for the southern and northern mountain slopes, respectively (Rossi and Villani, 1994).

Severe storms frequently affect the study area, triggering shallow landslides that propagate seaward, often causing casualties and serious damage to urbanized areas and transportation facilities (Mele and Del Prete, 1999; Calcaterra and Santo, 2004; Di Crescenzo and Santo, 2005). In the second half of the XX century, several shallow landslides activated nearby Castellammare di Stabia: in Table 1,
the major events recorded between Vico Equense and Gragnano are listed, with details on types of
events, affected sites and references. Shallow landslides listed in Table 1 occurred between
November and March, a period characterised by a medium to low suction range and included in the
rainy season (October to April), according to Cascini et al. (2014). The same Authors pointed out
that, in this period, frontal rainfall typically occurs and may trigger widespread first-time shallow
landslides, later propagating as debris flow or debris avalanches.

Rainfall responsible for landslide occurrences in the Sorrento Peninsula are shown in Fig. 7, in
terms of cumulated antecedent rains, extracted from the records of the nearest gauges (Tramonti,
Castellammare, and Tramonti-Chiunzi – cf. Fig. 6). The trends of antecedent rains look quite
different, ranging from abrupt (cf. curves 5, 6, 7) to progressive increases (cf. 2, 4, 10). On the other
hand, the curve 0 does not highlight significant amounts of rainfall in the 14 days preceding
landslide activation: therefore, the occurrence recorded on 14 April 1967 was excluded by the
hydrological analysis. Quite moderate amounts of cases 6 and 7 (occurred on 4 November 1980 and
14 November 1982, resp.) were instead recorded in short periods, thus resulting into high-intensity
events that could be considered as triggering factor of the observed landslides.

As a result, the dates of activation from #1 to #10 were selected for calibration, whilst #11 was
employed for validation. As shallow landslides were being considered, the rainfall period employed
for calibration spanned from 17 January 1963 to 10 December 1996; for validation, the rainfall
series extended from 11 December 1996 to 10 February 1997 – i.e., to the validation date +t_b (this
latter as obtained from calibration).

4.2 The Uncino landslide - San Fili (Northern Calabria)

San Fili (Fig. 8) is located on the western margin of the Crati graben, a tectonic depression along
the active Calabrian-Sicilian Rift Zone (Monaco and Tortorici, 2000). In the area, vicarious, N-S
trending normal faults mark the base of the Coastal Chain, at the transition between Palaeozoic
metamorphic rocks, to the West, and Pliocene-Quaternary sediments, to the East (Amadio Morelli
et al., 1976). Nearby San Fili, Palaeozoic migmatitic gneiss and biotitic schist, generally weathered,
are mantled by a Late Miocene sedimentary cover of reddish continental conglomerate, followed by
marine sandstone and clays (CASMEZ, 1967). In particular, the village lies in the intermediate
sector between two faults, marked by a NE-SW trending connection fault, delimiting Miocene
sediments, to the North, from gneissic rocks, to the South.

In Calabria, the Tyrrenhian sector (including the study area) results rainier than the Ionian (about
1200-2000 mm vs. 500 mm). Nevertheless, the most severe storms occur more frequently in the
Ionian sector (Terranova, 2004). The average annual temperature is about 15°C: the coldest months
are January and February (on average, 5°C), followed by December (8°C); the hottest months are
July and August (24°C), followed by June (22°C).

As in most of the region, the climate at San Fili is Mediterranean (Csa, according to Köppen, 1948).
Being located on the eastern side of a ridge, the area is subject to Föhn conditions with respect to
perturbations coming from the Tyrrenhian sea. It is characterized by heavy and frequent Winter
rainfall, caused by cold fronts mainly approaching from North-West, and Autumn rains, determined
by cold air masses from North-East. In Spring, rains show lower intensities than in Autumn, whilst
strong convective storms are common at the end of Summer. The average monthly rains recorded at
the Montalto Uffugo gauge (the closest to San Fili) are listed in Table 3. From October to March
(i.e., the wet semester), 77% of the annual rainfall is totaled in about 77 rainy days; 36% of the
annual rainfall is recorded in 38 days during the three wettest months; finally, from June to August (i.e., the three driest months), 6% of the annual rains fall in 11 days.

The Uncino landslide is located at the western margin of San Fili (Fig. 8). It is a medium-size rock slide (maximum width = 200 m, length > 650 m, estimated maximum vertical depth = 25 m), with a deep-seatedness factor (sensu Hutchinson, 1995) that may be classified as “intermediate”. The slope movement involves Late Miocene conglomerate, arenite and marly clay overlaying Palaeozoic gneiss and biotitic schist. It repeatedly affected the village, damaging the railway and the local road network, besides some buildings: the ancientmost known activation dates back to the beginning of the XX Century (Sorriso-Valvo et al., 1996); from 1960 to 1990, seven dates of mobilization are known (as listed in Table 2). On such events, the railroad connecting Cosenza to Paola was damaged or even interrupted. By the way, on 28 April 1987, the railway was put out of service, hence the relevance of the infrastructure decreased, together with media attention. Usually, such type of information is collected from archives not compiled by landslide experts, and is therefore affected by intrinsic uncertainty (e.g., concerning the dates of activity, and the partial or total activation of the phenomenon), with unavoidable problems of homogeneity of the data employed for model calibration.

The informative content of the Uncino case study is quite high, and allows for a more accurate calibration of the kernel with respect to the Sorrento Peninsula case: consequently, a smaller family of optimal solutions is expected. Nevertheless, the known activations still suffer from uncertainties related to dates and affected volumes.

Cumulated antecedent rains, corresponding to the Uncino landslide occurrences, are shown in Fig. 9. Rainfall data were extracted from the records of the Montalto Uffugo rain gauge (cf. Fig. 8). The trends of antecedent rains may be distinguished into 3 main patterns: the curve 2 shows a constant increase of rainfall in time, totalizing the greatest amounts from ca. 90 to 180 days. On the other hand, the case 0 shows the lowest values throughout the considered accumulation period. The curves 1, 3, 4, and 5 totalize intermediate values, with abrupt increases from 120 to 180 days for curves 3 and 5. Finally, the case 6 looks similar to case 2 between 30 and 90 days, but shows no more increases in the remaining period (analogously to 1 and 4).

As the curve 0 does not highlight significant amounts of rainfall in the 30-180 days preceding the landslide activation, the occurrence recorded on 23 November 1988 was excluded from the hydrological analysis. Of the remaining curves, case 1 generally shows the lowest amounts from ca. 40 to 180 days. Consequently, the dates of activation from #1 to #5 were selected for calibration, whilst #6 was employed for validation. Since a medium-size landslide was being considered, the rainfall period employed for calibration spans from 1 September 1959 to 31 August 1980; for validation, it ranges from 1 September 1980 to 31 March 1981 – i.e., including the validation date by ±t_{b} (this latter as obtained from calibration).

5 RESULTS

GASAKe was applied to shallow-landslide occurrences in the Sorrento Peninsula and to a medium-size slope movement at San Fili, by considering the dates of activation and the daily rainfall series mentioned in section §4.1 and §4.2, and adopting the values of parameters listed in Table 4.

Among the kernels obtained from calibration, several provided similar fitness values. Thus, “average kernels” were computed for the considered case studies, by averaging the best 100 kernels.

5.1 Application to shallow landslides in the Sorrento Peninsula
In Table 5, the statistics related to the best 100 filter functions obtained from calibration (optimal kernels) are summarized. From such values, a low variability of $\Phi$, $t_b$ and $\mu_0$ can be appreciated; instead, $\Delta z_{cr}$ shows a greater range of values. The average kernel is shown in Figure 10: it is characterized by fitness $= 0.806$, $\Delta z_{cr} = 0.00282$, and $t_b = 28$ days. From such kernel, antecedent rainfall mostly affecting landslide instability range from 1 to 12 days, and subordinately from 25 to 26 days (negligible weights refer to rains occurred in the remaining period).

The mobility function related to the average kernel is shown in Fig. 11. In this case, 4 out of 10 dates of landslide activation are well captured by the model (being ranked at the first 7 positions of the mobility function maxima); the remaining 6 dates do also correspond to relative maxima of the function, but are ranked from the 43rd to the 151st position. When considering the remaining relative maxima, several false positives can be recognized, mainly up to 1979.

During calibration, the best fitness ($\Phi = 0.807$) was first reached after 1749 iterations (at 6th individual), with $\Delta z_{cr} = 0.00441$ and $t_b = 26$ days. The kernel corresponding to such individual looks similar to the best one in terms of $t_b$, $\Delta z_{cr}$, and $\mu_0$ (Fig. 12). The pattern of the best kernel is only slightly dissimilar from the average one: significant weights can, in fact, be appreciated up to 14 days, and then between 20-22 and 25-26 days.

By applying the average kernel, a validation was performed against the remaining date of activation (cf. Table 1, #11, multiple event occurred on 10 January 1997). Validation resulted fully satisfied, as shown in Fig. 13: the value of the mobility function for the event #11 is well above the $z_{cr}$ threshold (49.01 vs. 18.05), and is ranked as the second highest value among the function maxima (Fig. 13a). The same peak can also be appreciated as the maximum of the period $\pm t_b$ (Fig. 13b). Accordingly, if adopting the average kernel, the event #11 of landslide activation could properly be predicted by the model.

5.2 Application to the Uncino landslide

In Table 6, the statistics related to the family of optimal kernels are summarized. From such values, a low variability of $t_b$ and $\Delta z_{cr}$ can be appreciated. The average kernel (Fig. 14) is characterized by fitness $= 1$, $\Delta z_{cr} = 0.0644$, and $t_b = 66$ days. Based on such kernel, antecedent rains from 1 to 17 days, and from 27 to 45 days, mainly affect landslide instability. Relatively smaller weights pertain to the rains occurred more than 53 days before the triggering; for periods older than 66 days, the weights are negligible.

In Fig. 15, the mobility function related to the average kernel highlights that all the 5 dates of activation are well captured by the model (they are ranked at the first 5 positions among the function maxima). When considering the remaining relative maxima of the function, only 4 of them evidence quasi-critical situations (between 1965 and 1966, and subordinately in 1970 and 1977). During calibration, the best fitness ($\Phi = 1$) was first reached after 684 iterations (at 13th individual) with $\Delta z_{cr} = 0.0595$. The best kernel (Fig. 16) was obtained at iteration 993, at 8th individual, with $\Delta z_{cr} = 0.0631$. Its pattern results very similar to the average one, with a $t_b$ of 66 days.

By applying the average kernel, a validation was performed against the last known date of activation (cf. Table 2, #6, occurred on December 1980). Validation resulted fully satisfied, as shown in Fig. 17: the value of the mobility function for the event #6, in fact, is well above the $z_{cr}$ threshold (17.49 vs. 16.87), and is ranked as the sixth highest value among the function maxima (Fig. 17a). The same peak can be appreciated as the maximum of the period $\pm t_b$ (Fig. 17b). Accordingly, if adopting the average kernel, the event #6 could properly be predicted by the model.
SELF-ADAPTIVE PROCEDURE AND SENSITIVITY ANALYSES

The capability of the model to react and self-adapt to input changes, such as new dates of landslide activation, was evaluated by a progressive, self-adaptive procedure of calibration and validation, using the information available for the Uncino case study. To simulate the adoption of GASAKe in a landslide warning system, the model was iteratively calibrated by the first 2, 3, 4, and 5 dates of activation (L), and validated against the remaining 4, 3, 2, 1 dates, respectively. In each experiment, the GA-parameters listed in Table 4 were adopted. Finally, the model was merely calibrated by considering all the 6 dates of activation. The results of the self-adaptive procedure are listed in Table 7. The related kernels are shown in Fig. 18. As a result, a progressive increase in fitness and predictive ability (∆zcr), together with the base time (ranging from 30 to 80 days), can be appreciated when employing a greater number of dates of activation.

Furthermore, aiming at evaluating the sensitivity of the model with respect to the GA parameters, a series of analyses was performed by considering again the Uncino case study. The experiments carried out are listed in Table 8. Each simulation stopped after 1500 iterations: GA-parameters were initialized by considering the “benchmark experiment” (cf. values in Table 4), except for the parameter that was in turn varied, as indicated in Table 8. The obtained maximum fitness (Φmax), safety margin (Δzcr), number (ni) of iterations needed to first reach Φmax, and base time (tb) of the average kernel are shown in Fig. 19. If experiments with Φmax = 1 are only taken into account, the minimum and maximum numbers of GA-iterations needed to reach Φmax (min Λ, max Λ), the minimum and maximum base times of the average kernel (min tb, max tb), and the minimum and maximum safety margins of the average kernel (min Δzcr, max Δzcr) are listed in Tables 9, 10 and 11, respectively.

DISCUSSION E CONCLUSIONS

In the present paper, the model GASAKe is presented with examples of application to shallow-landslides in Sorrento Peninsula (Campania), and to the medium-size Uncino landslide at San Fili (Calabria). Furthermore, the capability of the model to simulate the occurrence of known landslide activations was evaluated by a progressive, self-adaptive procedure of calibration and validation against the Uncino case study. Finally, the sensitivity of the model with respect to the GA parameters was analysed by a series of experiments, performed again by considering the latter landslide.

As concerns the Sorrento Peninsula case study, the maximum fitness obtained during calibration is smaller than unity. For the best 100 kernels, Φmax, Δzcr and tb vary in a small range (ca. 0.1%, 4.8%, and 13%, respectively). Furthermore, as mentioned above, for specific types of application (e.g., civil protection), the observed small values of Δzcr would imply short warning times. Consequently, a suitable kernel should be rather selected by privileging the shortest tb or the smallest µ0. From Fig. 12, it can be noticed that the greatest weights for the first 12-15 days are obtained by selecting the kernel characterized by the smallest µ0, thus allowing for the most timely advice if used within an early-warning system. In the average kernel, the greatest weight can be attributable to the first 12 days, with a maximum base time of about 4 weeks, reflecting the general shape of the curves in Fig. 7, and in good agreement with the shallow type of slope instability considered. Furthermore, the validation of the average kernel is satisfactory, as the validation date (#11 in Table 1) corresponds to the second highest peak of the mobility function. In addition, no missing alarms and only four
false alarms in about 5 years are to be found (i.e., in the period from the last date used for
calibration to the one for validation). The peaks of the mobility function corresponding to the
activation dates can roughly be grouped in two sets, characterized by distinct values: a first set, with
\(z(t)>40\), generally includes the ancientmost plus the validation dates (#1, #2, #4, #5, #6, and #11); a
second set (#3, #7, #8, #9, and #10), with \(18<z(t)<25\). False alarms result more frequent and higher
in the first period (from 1963 to 1980), presumably due to a lack of information on landslide
activations.

Regarding the Uncino case study, the maximum fitness in calibration reaches unity. With respect to
the Sorrento Peninsula case study, \(\Delta z_{cr}\) and \(t_b\) of the best 100 kernels vary in a greater range (ca.
25%, and 30.5%, respectively), with \(\Delta z_{cr}\) one order of magnitude greater. In this case, the kernel
would in fact allow for a safety margin of ca. 5%. In the average kernel, three main periods can be
recognized with heavier weights, attributable to (i) the first 17 days, (ii) 27-45 days, and (iii) 54-58
days. The base time ranges from about 8 to 12 weeks, in good agreement with the medium-size type
of the considered slope instability. Furthermore, the validation of the average kernel performed
successfully: in fact, the validation date (#6 in Table 2) corresponds to the third highest peak of the
mobility function; even in this case, neither missing alarms nor false alarms in about 2 years (from
the last date calibration date to the validation one) are to be found. The peaks of the mobility
function corresponding to the activation dates are characterized by \(z(t)>18\).

In the self-adaptive procedure applied to the Uncino case study, values for \(L=6\) merely refer to
calibration, whilst the ones for \(2\leq L\leq 5\) concern validation. With regard to Table 7 and Fig. 20, it can
be noticed that:

- for \(2\leq L\leq 5\), \(t_b\) increases 2.7 times with \(L\), and then remains constant for \(L\geq 5\);
- from \(L=2\) to \(L=4\), \(z_{j-min}\) and \(z_{cr}\) slightly decrease, and then abruptly increase for \(L\geq 5\);
- for \(L\geq 4\), \(\Delta z_{cr}\) monotonically increases 72 times with \(L\) (being almost constant in the 2-4
transition);
- \(\Phi\) monotonically increases 1.7 times with \(L\).

As a whole, a satisfying performance is obtained starting from 3 dates (i.e., correct predictions in
more than 3 out of 4 times). For \(L=5\), only one false alarm is observed. Finally, the calibration
performed by considering all the 6 dates of activation provided fully satisfying results. Accordingly,
the results of the progressive procedure underlined how \(^G^A^S^A^K^e\) can easily self-adapt to external
changes by optimizing its performances, providing increasing fitness values.

The average kernels obtained by considering from 2 to 6 dates of landslide activation show
increasing base times, with significant weights for the ancientmost rains of the temporal range (Fig.
18). Such result is in good accordance with the extent of the slope movement and, therefore, with
the expected prolonged travel times of the groundwater affecting landslide activation.

In the sensitivity analyses, again performed by considering the Uncino landslide, \(\Phi_{max}=1\) was
obtained in 60% of the experiments (cf. Table 8). The results (cf. Fig. 19 and Tables 9, 10, and 11)
permit to select the set of parameters that allow for faster GA performances. More in detail:

- a ratio between the number of elitist individuals and the whole population of \(n_e/N=10/20\) or
\(8/15\) allow for the fastest GA performances (\(min_{\Lambda_i}\approx 41\%\) of the reference value);
- nevertheless, for increasing both \(n_e\) and \(N\), this effect seems to vanish (e.g., \(n_e/N=12/25\));
- with respect to the benchmark experiment, the explored changes in \(p_c, pm, pmh1, pme\), and \(pm\) do
not substantially affect the GA performances with respect to \(min_{\Lambda_i}\).
• with respect to the benchmark experiment, the explored changes of parameters determine variation of \( t_b \) from 66 to 219%;

• in case of civil protection applications, the combination of parameters with \( p_{mh1} = 55 \) allows for activating early-warning procedures with the greatest advance;

• concerning \( \text{max}_\Delta \Delta z_{cr} \), the best result (increase by 10 times) is obtained when reducing \( N \) to 15.

The calibration experiments discussed in this paper were performed on a standard PC platform (CPU 3 GHz, RAM 4 GB, standalone system SQL and application process). For the study cases of Sorrento Peninsula and Uncino landslide, 2.5 and 1.1 GA-iterations were respectively performed per minute, reaching \( \Phi_{\text{max}} \) in 11\(^h\)40\(^m\) and 10\(^h\)20\(^m\). Depending on availability of High-Performance Computing Clusters, the mentioned durations may strongly be reduced, thus allowing for prompt Civil Protection applications, e.g. based on short-term weather forecasts. By the way, the time needed to calibrate the model can profitably be shortened by properly initializing the kernel, based on expected characteristics of the phenomena under consideration (e.g., the range of \( t_b \) strongly depends on landslide size).

In this study, a 2-steps efficiency criterion was employed: the relative position of the peaks of the mobility function with respect to the dates of landslide activation was first considered, and the fitness computed. Based on the value of \( \Delta z_{cr} \), the obtained solutions were further ranked. Average, synthetic filter functions could then be computed by selecting the best 100 kernels for successive validation purposes. Alternative metrics (cf., among the others, Krause et al., 2005) for the fitness function are being tested. However, due to uncertainties concerning input data (i.e., rainfall and dates of landslide activation), the adoption of sophisticated techniques does not sound very promising. In addition, problems of over-fitting may depend on both data uncertainties and number of parameters. Commonly, kernels characterized by a complex pattern (and then by many parameters) are needed for simulating groundwater dynamics (Pinault et al., 2001). Nevertheless, more complex kernels do not necessarily imply higher predictive uncertainties (Fienen et al., 2010; Long, 2015). Still, the adopted discrete approach allows focusing only on the timing of the peaks of the mobility function, thus somehow relieving the computational effort. Due to the cited uncertainties in input data, a “temporal window” was in fact employed to help matching dates of activation with the peaks of the mobility function. Further attempts of defining the fitness function by different metrics, and the analysis of its effects on calibration and validation, are being considered against another case study (San Benedetto Ullano, in Calabria, Southern Italy), whose mobility phases have been recently monitored by the same authors (Iovine et al., 2010; Capparelli et al., 2012).

As mentioned above, model calibration may be hampered by either quality or completeness of input data. Commonly, missing dates of activation (mainly in remote periods or in isolated areas) and unsuitability of the rain gauge network (e.g., due to excessive distance of gauges from the landslides) negatively affect model results. Depending on availability of new dates of activation, stemming from further mobilizations or improvement of historical investigations, the predictive capability of the model can be increased through additional calibrations, hence providing new families of optimal solutions, constituted by fewer, highly significant kernels.

The above considerations suggest an indirect link between the model – despite empirical in type – and the physical characteristics of the slope movements (e.g., dimensions, permeability, initial water content of the slope, length of subsurface water paths). In general, to select the kernel to be
applied, it is rather preferable to consider a set of optimal kernels or the average one, instead of a single solution.

Further efforts are in progress to improve the model and its chances of practical application, mainly concerning the implementation of different GA techniques of optimization (in addition to the elitist, here employed), the parallelization of the model, and the adoption of a Genetic Programming approach. Finally, through the analytical study of the optimal kernels, a mathematical formulation of discrete filter functions is presently being attempted, aiming at synthetizing optimal and average kernels for an easier comparison with the results of other models available in literature.

8 CODE AVAILABILITY

The release G4SAKe of the Self Adaptive Kernel model, discussed in this paper, has been developed by scientists working at CNR-IRPI under Microsoft Windows, Visual Studio, and SQL Server integrated development environment. It can be requested by the public to the corresponding author of the paper, together with examples of input data and technical support (a user manual is not available yet, but it should be released soon). The model is presently undergoing further refinements and developments, mainly concerning types of GA-selection techniques, the post-processing of the results in terms of continuous analytical functions, and the implementation of a library of case studies. Authors are willing to cooperate with external users to further improving the model through applications to case studies from different geo-environmental contexts.

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REFERENCES


Cascini, L., Sobbino, G., Cuomo, S., Ferlisi, S.: Seasonal effects of rainfall on the shallow pyroclastic deposits of the Campania region (southern Italy), Landslides, 11, 779-792, 2014.


Gullà, G., Aceto, L., Antronico, L., Cilento, M., Niceforo, D., Perna, E., and Terranova, O.: Failure and post failure conditions of a landslide involving weathered and degraded rocks, in


Köppen,W.: Climatologia, con un studio de los climas de la tierra, Fondo de Cultura Economica, Mexico, 479 pp., 1948.


Table 1. Dates of activation of the shallow landslides in the Sorrento Peninsula. Key: date = day of occurrence; type = widespread (multiple) or few (single) activation; site = municipality including the affected location; period employed = dates used for calibration (except for #11); rank = relative position of the corresponding maximum of the mobility function obtained by calibration. An asterisk marks the date employed for validation. In Italics, the activation date (#0) excluded due to hydrological constraints.

<table>
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<tr>
<th>#</th>
<th>Date</th>
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<th>site</th>
<th>reference</th>
<th>period employed</th>
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<td>Del Prete et al. 1998</td>
<td>17 Feb 1963</td>
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<td>single</td>
<td>Castellammare (Pozzano)</td>
<td>Del Prete et al. 1998; AMRA, 2012</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>02 January 1971</td>
<td>single</td>
<td>Gragnano</td>
<td>Del Prete et al. 1998</td>
<td>02 Jan 1971</td>
<td>3 Jan 1971 (3)</td>
</tr>
<tr>
<td>8</td>
<td>22 February 1986</td>
<td>multiple</td>
<td>Palma Campania, Castellammare, Vico Equense</td>
<td>Del Prete et al. 1998</td>
<td>22 Feb 1986</td>
<td>24 Feb 1986 (120)</td>
</tr>
<tr>
<td>11</td>
<td>10 January 1997</td>
<td>multiple</td>
<td>Pozzano; Castellammare, Nocera, Pagani, Amalfitana Coast</td>
<td>Del Prete et al. 1998; AMRA, 2012</td>
<td>10 Jan 1997</td>
<td>*</td>
</tr>
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Table 2. Dates of activation of the Uncino landslide. Periods (instead of singular dates) were considered in case of uncertain timing of activation. Key = #: Identification number of the date (in bold, used for calibration); dates/periods derived from literature; dates/periods employed for calibration or validation; references: sources of information on activation dates; rank: relative position and dates of the maxima of the mobility function during calibration. An asterisk marks the activation employed for validation. In Italics, the activation date (#0) excluded due to hydrological constraints.

<table>
<thead>
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</tr>
<tr>
<td>5</td>
<td>10-14, 21 February 1979</td>
<td>Sorriso-Valvo et al., 1994</td>
<td>10-21 Feb 1979</td>
<td>15 Feb 1979 (4)</td>
</tr>
<tr>
<td>6</td>
<td>December 1980</td>
<td>Sorriso-Valvo et al., 1994</td>
<td>01-31 Dec 1980</td>
<td>*</td>
</tr>
<tr>
<td>0</td>
<td>23 November 1988</td>
<td>Sorriso-Valvo et al., 1996</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3. Average monthly rainfall and number of rainy days at the Montalto Uffugo rain gauge (468 m a.s.l.).

<table>
<thead>
<tr>
<th></th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>rainfall (mm)</td>
<td>70.4</td>
<td>125.1</td>
<td>187.9</td>
<td>220.8</td>
<td>198.1</td>
<td>160.3</td>
<td>132.8</td>
<td>98.9</td>
<td>64.6</td>
<td>27.8</td>
<td>18.3</td>
<td>28.6</td>
<td>1333.6</td>
</tr>
<tr>
<td>rainy days</td>
<td>6.9</td>
<td>10.6</td>
<td>12.8</td>
<td>14.3</td>
<td>14.3</td>
<td>12.5</td>
<td>12.6</td>
<td>10.7</td>
<td>8.26</td>
<td>4.7</td>
<td>2.62</td>
<td>3.84</td>
<td>114.0</td>
</tr>
</tbody>
</table>
Table 4. Values of the parameters of $G^dSAKe$ adopted in the calibration procedure (benchmark experiment).

<table>
<thead>
<tr>
<th>symbol</th>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>individuals of each GA population</td>
<td>20</td>
</tr>
<tr>
<td>$t_b$</td>
<td>base time (Uncino landslide)</td>
<td>30 ÷ 180 days</td>
</tr>
<tr>
<td>$t_b$</td>
<td>base time (shallow landslides in the Sorrento Peninsula)</td>
<td>2 ÷ 30 days</td>
</tr>
<tr>
<td>$p_mh1$</td>
<td>percentages of the maximum height of the kernel, used to defining the range in which $dh$ is randomly obtained</td>
<td>50%, 150%</td>
</tr>
<tr>
<td>$p_mh2$</td>
<td>probability of crossover</td>
<td>75%</td>
</tr>
<tr>
<td>$p_c$</td>
<td>probability of mutation</td>
<td>25%</td>
</tr>
<tr>
<td>$p_m$</td>
<td>number of mutated elements of the kernel, expressed as a percentage of $t_b$</td>
<td>25%</td>
</tr>
<tr>
<td>$p_mthb$</td>
<td>factor defining the range in which $dt_b$ is selected</td>
<td>0.2 ÷ 5</td>
</tr>
<tr>
<td>$A$</td>
<td>number of GA-iterations (Uncino landslide case study)</td>
<td>5000</td>
</tr>
<tr>
<td>$n_e$</td>
<td>number of GA-iterations (Sorrento Peninsula case study)</td>
<td>3000</td>
</tr>
<tr>
<td>$n_e$</td>
<td>number of &quot;elitist&quot; individuals</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 5. Sorrento Peninsula case study. Statistics for the best 100 kernels.

<table>
<thead>
<tr>
<th></th>
<th>$\Phi$</th>
<th>$\Delta z_c$</th>
<th>$t_0$</th>
<th>$\mu_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.806</td>
<td>3.82E-05</td>
<td>26.0</td>
<td>9.460</td>
</tr>
<tr>
<td>average</td>
<td>0.806</td>
<td>0.00418</td>
<td>30.4</td>
<td>9.567</td>
</tr>
<tr>
<td>max</td>
<td>0.807</td>
<td>0.00801</td>
<td>31.0</td>
<td>10.448</td>
</tr>
<tr>
<td>median</td>
<td>0.806</td>
<td>0.00499</td>
<td>31.0</td>
<td>9.567</td>
</tr>
<tr>
<td>mode</td>
<td>0.806</td>
<td>0.00499</td>
<td>31.0</td>
<td>9.567</td>
</tr>
<tr>
<td>dev. st.</td>
<td>7.65E-05</td>
<td>0.00183</td>
<td>0.862</td>
<td>0.146</td>
</tr>
</tbody>
</table>
Table 6. Uncino landslide case study. Statistics for the best 100 kernels.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta z_{cr}$</th>
<th>$t_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.0524</td>
<td>57.0</td>
</tr>
<tr>
<td>average</td>
<td>0.0581</td>
<td>69.5</td>
</tr>
<tr>
<td>max</td>
<td>0.0692</td>
<td>82.0</td>
</tr>
<tr>
<td>median</td>
<td>0.0581</td>
<td>69.0</td>
</tr>
<tr>
<td>mode</td>
<td>0.0558</td>
<td>69.0</td>
</tr>
<tr>
<td>dev. st.</td>
<td>0.00373</td>
<td>3.12</td>
</tr>
</tbody>
</table>
Table 7. Uncino landslide case study. Results of progressive calibration. Key: \( L, t_0, z_{j_{\text{init}}}, z_{cr}, \Delta z_{cr} \): model parameters concerning calibration (for explanation, cf. text); \( \Phi_i \): fitness obtained by validating the “average kernel”, obtained in calibration, against the 6 dates of activation. In Italics, results obtained when calibrating the model by using all the 6 available dates (no validation performed).

<table>
<thead>
<tr>
<th>( L )</th>
<th>( t_0 )</th>
<th>( z_{j_{\text{res}}} )</th>
<th>( z_{cr} )</th>
<th>( \Delta z_{cr} )</th>
<th>( \Phi_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>30</td>
<td>13.93</td>
<td>13.89</td>
<td>0.0029</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>11.05</td>
<td>11.04</td>
<td>0.0009</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>10.21</td>
<td>10.20</td>
<td>0.0010</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>16.44</td>
<td>16.34</td>
<td>0.0061</td>
<td>0.95</td>
</tr>
<tr>
<td>6</td>
<td>80</td>
<td>18.63</td>
<td>17.43</td>
<td>0.0644</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table 8. Uncino landslide case study. Values of the parameters adopted in the sensitivity analyses. In bold, the experiments with $\Phi_{\text{max}} = 1$. Boxes evidence the worst experiment (in Italics), and the best one (underlined).

<table>
<thead>
<tr>
<th>symbol</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c$</td>
<td>6</td>
</tr>
<tr>
<td>$p_c$</td>
<td>60%</td>
</tr>
<tr>
<td>$p_a$</td>
<td>20%</td>
</tr>
<tr>
<td>$p_{\text{abd}}$</td>
<td>60%, \textbf{55}%</td>
</tr>
<tr>
<td>$p_{\text{abd}}$</td>
<td>140%</td>
</tr>
<tr>
<td>$p_{\text{m}}$</td>
<td>20%</td>
</tr>
<tr>
<td>$p_{\text{mtb}}$</td>
<td>\textbf{0.25} ÷ 4</td>
</tr>
<tr>
<td>$N, n_e$</td>
<td>\underline{25}, 8</td>
</tr>
<tr>
<td>$N, n_e$</td>
<td>25, 12</td>
</tr>
</tbody>
</table>

* Reference values (i.e., those of the benchmark experiment - cf. Table 4)
Table 9. Minimum ($min_{\Lambda_i}$) and maximum ($max_{\Lambda_i}$) numbers of GA iterations needed to reach $\Phi_{\text{max}}$ (only experiments with $\Phi_{\text{max}} = 1$ are considered). In the first column, the letters refer to Fig. 19. In bold, the best and worst experiments. An asterisk marks the experiment $e$, in which $\Phi_{\text{max}}$ was reached only for $p_c=75$. In Italics, the combinations of parameters of the benchmark experiment (cf. Table 4).

<table>
<thead>
<tr>
<th>§</th>
<th>N</th>
<th>parameter</th>
<th>$min_{\Lambda_i}$</th>
<th>$max_{\Lambda_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>20</td>
<td>$n_e=8$</td>
<td>279</td>
<td>684</td>
</tr>
<tr>
<td>a</td>
<td>20</td>
<td>$n_e=10$</td>
<td>469</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>25</td>
<td>$n_e=8$</td>
<td>1477</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>20</td>
<td>$p_c=75$</td>
<td>684*</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>20</td>
<td>$p_m=25$</td>
<td>684</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>20</td>
<td>$p_m=27.5$</td>
<td>1086</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>20</td>
<td>$p_{\text{m}}=50$</td>
<td>684</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>20</td>
<td>$p_{\text{m}}=55$</td>
<td>836</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>20</td>
<td>$p_{\text{m}}=25$</td>
<td>684</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>20</td>
<td>$p_{\text{m}}=30$</td>
<td>996</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>20</td>
<td>$p_{\text{m}}=5$</td>
<td>684</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>20</td>
<td>$p_{\text{m}}=5.5$</td>
<td>1052</td>
<td></td>
</tr>
<tr>
<td>o</td>
<td>15</td>
<td>$n_e=8$</td>
<td>405</td>
<td></td>
</tr>
</tbody>
</table>
Table 10. Minimum \((min_{tb})\) and maximum \((max_{tb})\) base time of the average kernel (only experiments with \(\Phi_{\text{max}} = 1\) are considered). In the first column, the letters refer to Fig. 19. In bold, the best and worst experiments. An asterisk marks the experiment \(e\), in which \(\Phi_{\text{max}}\) was reached only for \(p_{mc}=75\). In Italics, the combinations of parameters of the benchmark experiment (cf. Table 4).

<table>
<thead>
<tr>
<th>(s)</th>
<th>(N)</th>
<th>(N_{e})</th>
<th>(min_{tb})</th>
<th>(max_{tb})</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>20</td>
<td>8</td>
<td>66.59</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>20</td>
<td>10</td>
<td></td>
<td>144.85</td>
</tr>
<tr>
<td>c</td>
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<td>132.00</td>
</tr>
<tr>
<td>c</td>
<td>25</td>
<td>12</td>
<td>56.17</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>20</td>
<td>(p_{mc}=73)</td>
<td>66.59*</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>20</td>
<td>(p_{mc}=25)</td>
<td>66.59</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>20</td>
<td>(p_{mc}=27.5)</td>
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<td>139.20</td>
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<tr>
<td>i</td>
<td>20</td>
<td>(p_{mc}=50)</td>
<td></td>
<td>66.59</td>
</tr>
<tr>
<td>i</td>
<td>20</td>
<td>(p_{mc}=55)</td>
<td><strong>44.00</strong></td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>20</td>
<td>(p_{mc}=25)</td>
<td>66.59</td>
<td></td>
</tr>
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<td>k</td>
<td>20</td>
<td>(p_{mc}=30)</td>
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<td><strong>146.93</strong></td>
</tr>
<tr>
<td>m</td>
<td>20</td>
<td>(p_{mc}=5)</td>
<td>66.59</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>20</td>
<td>(p_{mc}=4)</td>
<td></td>
<td>136.06</td>
</tr>
<tr>
<td>o</td>
<td>15</td>
<td>8</td>
<td></td>
<td>145.79</td>
</tr>
</tbody>
</table>
Table 11. Minimum ($\text{min}_{\Delta z_{cr}}$) and maximum ($\text{max}_{\Delta z_{cr}}$) safety margin of the average kernel (only experiments with $\Phi_{max} = 1$ are considered). In the first column, the letters refer to Fig. 19. In bold, the best and worst experiments. An asterisk marks the experiment $e$, in which $\Phi_{max}$ was reached only for $p_{c} = 75$. In Italics, the combinations of parameters of the benchmark experiment (cf. Table 4).

<table>
<thead>
<tr>
<th>$$</th>
<th>$N$</th>
<th>parameter</th>
<th>$\text{min}<em>{\Delta z</em>{cr}}$</th>
<th>$\text{max}<em>{\Delta z</em>{cr}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>20</td>
<td>$n_e = 7$</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>20</td>
<td>$n_e = 9$</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>25</td>
<td>$n_e = 8$</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>25</td>
<td>$n_e = 12$</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>20</td>
<td>$p_c = 75$</td>
<td>0.005*</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>20</td>
<td>$p_a = 22.5$</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>20</td>
<td>$p_a = 27.5$</td>
<td><strong>0.001</strong></td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>20</td>
<td>$p_m = 50$</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>20</td>
<td>$p_m = 55$</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>20</td>
<td>$p_m = 25$</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>20</td>
<td>$p_m = 30$</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>20</td>
<td>$p_m = 5$</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>20</td>
<td>$p_m = 4$</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>o</td>
<td>15</td>
<td>$n_e = 8$</td>
<td><strong>0.055</strong></td>
<td></td>
</tr>
<tr>
<td>o</td>
<td>20</td>
<td>$n_e = 8$</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Scheme of the calibration procedure of the model $^{G.4}SAKe$. 
Figure 2. Scheme of the adopted Genetic Algorithm.

- Start
- Random generation of population of genotypes
- Fitness evaluation of each phenotype
- Selection of genotypes (based on fitness)
- Storage of selected genotypes into the mating pool
- Application of cross-over and mutation to all genotypes
- Fitness evaluation of new phenotypes
- iteration < ∞
  - No
  - Yes
  - Stop
Figure 3. Example of crossover. The genetic codes of the parents (elements in orange and green) are first mixed; then, the children are normalized (black elements) to ensure validity of equation 2.
**Figure 4.** Examples of mutation. On the left, the genetic code of the parent individual (elements in blue). In the second histogram, mutation is applied to some elements of the parent (in red, added amounts; in grey, subtracted amounts). Then, the base time can either be decreased (upper sequence) or increased (lower sequence). Finally, the children is normalized (black elements) to ensure validity of equation 2.
Figure 5. Scheme of the validation procedure of the model $G^4SAKe$. 
**Figure 6.** Geological map of the Sorrento Peninsula (after Di Crescenzo and Santo, 1999, mod.). Key: 1) beach deposit (Holocene); 2) pyroclastic fall deposit (Late Pleistocene-Holocene); 3) Campanian ignimbrite (Late Pleistocene); 4) detrital alluvial deposit (Pleistocene); 5) flysch deposit (Miocene); 6) limestone (Mesozoic); 7) dolomitic limestone (Mesozoic). Red squares mark sites affected by shallow landslide activations; blue circles, the rain gauges; black squares, the main localities; yellow triangles, the highest mountain peaks.
Figure 7. Cumulative daily rainfall (in mm) during the 14 days preceding landslide occurrences. Key: in blue, red, and green = values from the Tramonti, Castellammare, and Tramonti-Chiunzi rain gauges, respectively. Numbers refer to id. in Table 1 (cf. first column).
Figure 8. Location of the study area (red square: San Fili village; blue circle: Montalto Uffugo rain gauge). On bottom left, an extract from the geological map of Calabria (CASMEZ, 1967). Key: sbg) gneiss and biotitic schist with garnet (Palaeozoic); sbm) schist including abundant granite and pegmatite veins, forming migmatite zones (Palaeozoic); M₁⁰) arenite and silt with calcarenite (Late Miocene); M₁⁰) marly clay with arenite and marls (Late Miocene); m₁⁰) reddish conglomerate with arenite (Late Miocene); q⁰) loose conglomerate of ancient fluvial terraces (Pleistocene). The site affected by the Uncino landslide is marked by a red star.
Figure 9. Cumulative daily rainfall (in mm) from 30 to 180 days before landslide occurrences (Montalto Uffugo gauge). Numbers refer to identification number (#) in Table 2 (cf. first column).
Figure 10. Sorrento Peninsula case study. Average kernel obtained from the best 100 filter functions.
Figure 11. Sorrento Peninsula case study. Mobility function, $z(t)$, of the average kernel. The red line ($z_{cr} = 22.53$) shows the maximum value of the mobility function (critical condition) that is unrelated to known landslide activations. The green line ($z_{j-min} = 22.63$) – almost overlapping with the red line in this case – shows the minimum value of the mobility function related to known landslide activations. When the mobility function exceeds the threshold marked by the red line, landslide activation may occur. The red dots represent the maxima of the mobility function corresponding to the dates of landslide activation considered for calibration.
Figure 12. Sorrento Peninsula case study. Kernels providing (a) the best fitness ($\Phi_{\text{max}} = 0.807$), (b) the minimum base time $t_b\,\text{min}$ (26 days), (c) the $\Delta z_{cr\,\text{max}}$ (0.00801), and (d) the minimum first order momentum, $\mu_0\,\text{min}$ (9.460).
Figure 13. Sorrento Peninsula case study. a) Validation of the average kernel against the #11 event. b) Particular of Fig.13a, limited to the period $\pm t_0$, including the date of validation. Key as in Fig.11. The blue label indicates the date of validation. Grey background marks the period after the event that may be employed for re-calibration.
Figure 14. Uncino landslide case study. Average kernel obtained from the best 100 filter functions.
Figure 15. Uncino landslide case study. Mobility function, $z(t)$, of the average kernel. The red line ($z_{cr} = 17.85$) shows the maximum value of the mobility function (critical condition) that is unrelated to known activations. The green line ($z_{j_{min}} = 18.98$) shows the minimum value of the mobility function related to known activations. When the mobility function exceeds the threshold marked by the red line, landslide activation may occur. The red dots represent the maxima of the mobility function corresponding to dates of landslide activation considered for calibration.
Figure 16. Uncino landslide case study. Kernel providing the best fitness.
**Figure 17.** Uncino landslide case study. a) Validation of the average kernel against the #6 event. b) Particular of Fig.17a, limited to the period $\pm t_b$ including the date of validation. Key as in Fig. 15. The blue label indicates the date of validation. Grey background marks the period after the event that may be employed for re-calibration.
Figure 18. Uncino landslide case study. Average kernels obtained in calibration against the 2, 3, 4, 5, and 6 dates of activation.
Figure 19. Maximum fitness ($\Phi_{\text{max}}$), safety margin ($\Delta z_{cr}$), number ($n_i$) of iterations needed to first reach $\Phi_{\text{max}}$, and base time ($t_b$) of the average kernel, based on GA parameters listed in Table 8.
Figure 20. Uncino landslide case study. Results of progressive calibration. Variation of $\Delta z_{cr}$ and $\Phi_v$ for $L$ increasing from 2 to 6.