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Estimation of debris flow critical rainfall thresholds by a physically-based model

M. N. Papa[1], **V. Medina**[2], **F. Ciervo**[1], **and A. Bateman**[2]

[1]Department of Civil Engineering, University of Salerno, Salerno, Italy
[2]Sediment Transport Research Group, Hydraulic, Marine and Environmental Engineering Department, Technical University of Catalonia (UPC), Barcelona, Spain

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Correspondence to: M. N. Papa (mnpapa@unisa.it)

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Abstract

Real time assessment of debris flow hazard is fundamental for setting up warning systems that can mitigate its risk. A convenient method to assess the possible occurrence of a debris flow is the comparison of measured and forecasted rainfall with rainfall threshold curves (RTC). Empirical derivation of the RTC from the analysis of rainfall characteristics of past events is not possible when the database of observed debris flows is poor or when the environment changes with time. For landslides triggered debris flows, the above limitations may be overcome through the methodology here presented, based on the derivation of RTC from a physically based model. The critical RTC are derived from mathematical and numerical simulations based on the infinite-slope stability model in which land instability is governed by the increase in groundwater pressure due to rainfall. The effect of rainfall infiltration on landside occurrence is modelled trough a reduced form of the Richards equation. The simulations are performed in a virtual basin, representative of the studied basin, taking into account the uncertainties linked with the definition of the characteristics of the soil. A large number of calculations are performed combining different values of the rainfall characteristics (intensity and duration of event rainfall and intensity of antecedent rainfall). For each combination of rainfall characteristics, the percentage of the basin that is unstable is computed. The obtained database is opportunely elaborated to derive RTC curves. The methodology is implemented and tested on a small basin of the Amalfi Coast (South Italy).

1 Introduction

Rainfalls with peculiar characteristics of intensity and duration may trigger Debris Flows. These events are particularly dangerous for a number of reasons. Debris flows may travel for long distances, like water flows and the steep slopes induce high velocities. They may easily impact the conoid of mountain torrents that, especially in recent years and in some cases also in historical times, have been intensively urbanized. The density effect on the impact force of the debris flows makes it well higher than the one due to water flows and thus damages to buildings are proportionally greater. Predicting debris flows is quite difficult because there are no premonitory signs and the lag time between the occurrence of the triggering rainfall and the impact of the debris flow in the vulnerable downstream area is very short (about one hour).

The mitigation of debris flow hazards may be achieved building structural countermeasures, such as, check dams and retention basins. However, in some cases, the rigid topography of the interested areas, or the lack of space, makes it difficult to build structural countermeasures. Moreover, the impact of these works on the landscape may be rather high. This problem is particularly noted in areas with high environmental and historical value. For the aforementioned reasons, non structural countermeasures, such as warnings through real time hazard assessment and civil protection measures are more suitable in reducing the risks. Economic reasons can also influence the choice among the two as non-structural countermeasures are less expensive than structural ones. Due to the short lag time, this warning system must rely on forecasted and nowcasted rainfall. The warning is given when the forecasted rainfall overcomes a critical threshold.

The most common approach adopted in literature for the assessment of the rainfall critical thresholds (Caine, 1980; Wieczorek and Glade, 2005; Brunetti et al., 2010) is based on the elaboration of datasets of recorded historical events. The first limit of these approaches is the small range of application: in fact they may be adopted only for those basins where a certain amount of recorded debris flow events is available for the derivation of the empirical threshold line. Another drawback of empirically derived thresholds is that they cannot anticipate how debris flow hazards may change in response to changing environments, for example, land use changes, large forest fires and decrease of sediment availability. The last may be determined by a debris flow.

In order to overcome these limitations, it is necessary to estimate rainfall critical thresholds through a model that reflects the physics of the phenomenon and provides the link between rainfall and possible debris flow hazards. There are two types of formation mechanisms for rainfall triggered debris flow. The first type happens when a rainfall triggered landslide evolves into a proper flow causing a debris flow. The second one is the result of a progressive entrainment of bed sediments into a water flow. In the present paper we focused on the first kind as this formation mechanism occurs quite often in many different geological contexts (Iverson, 1997).

Theoretical models of rainfall triggered landslides are usually based on the infinite-slope stability analysis in which land instability is governed by the increase in groundwater pressure due to rainfall. These models are usually implemented in discrete landscape cells and compute the security factor for each one. Many of the approaches proposed in literature are based on the hypothesis of steady groundwater flow conditions (Montgomery and Dietrich, 1994). A simplified model has been proposed by Iverson (2000) to assess short term pore water response to rainfall in the hypothesis of vertical infiltration. Comparisons of models results with observed scars of debris flow formation areas (Godt et al., 2008) have shown that the Iverson model is more effective for regional shallow landslide hazard maps. However, the number of false positives and false negatives in the predicted unstable cells is still very high.

Casadei et al. (2003) coupled an infinite slope stability model with a dynamic hydrologic model inspired by the Topmodel (Beven and Kirkby, 1979). Simoni et al. (2008) proposed a model (GEOtop-FS) that compute soil moisture and matric suction within soil layers by numerically integrating Richards' equation in a 3-D-scheme. Another hydrological model (SHETRAN model) including a infinite slope stability module was developed by Bathurst et al. (2006). The models that compute the safety factor cell by cell, usually overestimate the potential instabilities because a single instable element is not going to move if it is surrounded by stable elements. In order to overcome this limitation, some authors (Lehmann and Or, 2012) developed techniques for the simulation of the cascade load redistributions that from initially localized failures evolve into successive failures propagating across the hillslope.

Distributed land stability models cannot be used in real time to predict the possible occurrence of a debris flow because of the long computational times. In addition if quantitative precipitation forecasting ensemble is used the computational runs should be multiplied. Moreover, with the aim of giving debris flow warnings, it is not necessary to know the distribution of instable elements along the basin but only if a debris flow may affect the vulnerable areas in the valley. The capability to reach the downstream areas depends on many factors linked with the topography, the solid concentration, the rheological properties of the debris mixture, the flow discharge and the occurrence of liquefaction of the sliding mass. Many of these factors are not time dependent. The most rainfall dependent factors are flow discharge and correlated total debris volume. In the present study, the total volume that is instable, and therefore available for the flow, is considered to be the governing factor from which it is possible to assess whether a debris flow will affect the downstream areas or not.

The approach presented is based on the simulation of a large number of cases covering the entire range of rainfall intensity, rainfall duration and antecedent rain and considering the different possible combinations between the three of them. The total debris volume, available for the flow, is computed in each simulation case. The resulting database is elaborated in order to obtain rainfall threshold curves. When operating in real time, if the observed and forecasted rainfall exceeds a given threshold, the corresponding probability of debris flow occurrence may be estimated. Warning for possible debris flow occurrence may be given congruently with these results.

2 Mathematical and numerical modelling

The possible triggering of a debris flow is simulated, in a generic element of the basin, by an infinite slope stability analysis (Iverson, 2000; Taylor, 1948). At any depth from the surface (Z), and at any time (t), the factor of safety (FS) is computed by the ratio between the resisting Coulomb friction and the driving stresses induced by gravity:

$$\mathrm{FS}(Z,t) = \frac{\tan\varphi}{\tan\alpha} + \frac{c - \Psi(Z,t)\gamma_{\mathrm{w}}\tan\varphi}{\gamma_{\mathrm{s}} Z \sin\alpha\cos\alpha}, \tag{1}$$

where α is the slope degree, Z is the vertical coordinate, positive downward, c is the soil cohesion, ϕ is the angle of internal friction, γ_{s} is the depth averaged soil unit weight, γ_{w} is the unit weight of ground water and $\psi(Z,t)$ is the underground water pressure head that depends on the vertical coordinate and time (t).

When a critical value of FS is reached (e.g. $\mathrm{FS} = 1$) the soil over the Z depth is considered unstable.

Many observed debris flow events have been triggered by a long term and low intensity rainfall followed by a short term-heavy rainfall (Crozier, 1989; Wieczorek and Glade, 2005). As a consequence, the triggering groundwater pressure is calculated by superimposing the effect of an "antecedent" rainfall and an "event" rainfall. The groundwater pressure response to antecedent rainfall is used as the initial condition for the time-dependent computation of the groundwater pressure response to the event rainfall.

If the antecedent rainfall has a sufficiently low intensity and long duration, the steady state conditions are reached and the direction of the groundwater flux may be assumed to be slope parallel. Under this condition, the ground water pressure, at the initial condition ($t = 0$), may be calculated by:

$$\Psi(Z,0) = (Z - d)\cos^2\alpha, \tag{2}$$

where d is the water table depth, measured in the Z direction, in steady state conditions. Following Montgomery and Dietrich (1994), the mass conservation equation of groundwater flow gives the following:

$$(Z_T - d) = \frac{(I_z)_{\mathrm{steady}}}{K_x}\frac{A}{b\sin\alpha\cos}\alpha, \tag{3}$$

where Z_T is the depth of the impermeable bed, $(I_z)_{\text{steady}}$ is the infiltration rate at ground surface in the normal slope direction, in steady conditions, K_x is the hydraulic conductivity in the parallel slope direction, A is the drained catchment, b is the width of the slope element along the direction tangent to the local topographic contour.

Following the approach of Iverson (2000), the short term response to rainfall may be assessed in the hypothesis of vertical infiltration. He proposed an analytical solution of a linearized Richards equation valid in the assumption of almost saturated initial conditions. The boundary conditions are: transient groundwater vertical flux equal to zero at great depths below the water table and water entry at ground surface governed by Darcy's law. In these conditions, the water pressure heads are given by (Iverson, 2000):

$$\Psi(Z,T) = \Psi(Z,0) + Z\frac{I_z}{K_z}\left[R(T^*)\right], \tag{4}$$

where T is the duration of the event rainfall, $\psi(Z,0)$ is the ground water pressure head at the beginning of the event rainfall, I_z is the infiltration rate at ground surface, in the normal slope direction, K_z is the hydraulic conductivity in the normal slope direction and $R(T^*)$ is defined as follows:

$$R(T^*) = \sqrt{\frac{T^*}{\pi}}\exp\left(\frac{-1}{T^*}\right) - \operatorname{erfc}\left(\frac{1}{\sqrt{T^*}}\right), \tag{5}$$

in which:

$$T^* = \frac{T}{\frac{Z^2}{(4D_0\cos^2\alpha)}}, \tag{6}$$

where D_0 is the maximum characteristic diffusivity, governing the transmission of pressure heads when the soil is near to saturation.

In many cases, a great increment of debris flow volume occurs as a consequence of channel erosion during the runout process. It means that a huge volume of sediment could be produced even if the debris flow is of a small size in the occurrence area. On the other hand, the single computational element that results unstable may not move if it is surrounded by stable elements. The possible development of a local instability into a debris flow is affected by the occurrence of liquefaction. All these phenomena are not taken into account by the model presented here.

2.1 Model implementation

In order to asses if a specific basin may give place to the formation of a debris flow, the instability simulation, previously described, is performed for a certain amount (n) of computational elements, randomly chosen, that approximate the behavior of the entire catchment. Low n values allow minimizing the computational time. For n exceeding 1 % of the total basin cells, the simulation results converge to the one obtained simulating all the basin cells.

The input variables that feed the model are divided into two main families, "static" and "dynamic". Static variables are the morphological features ($A/b, Z_T, \alpha$) and the soil parameters (c, ϕ, γ_s, K_x, K_z, D_0). These are considered as stationary at the process scale. The dynamic variables are the rainfall related variables ($(I_z)_{\text{steady}}$, I_z, T)

The uncertainties in the evaluation of the soil variables are taken into account assigning to each variable an average value along with a confidence interval. The assignment of a specific soil variable value to a certain number of input strings follows the normal distribution function of that variable having the assigned average and confidence interval.

The dynamic input variables $T, I_z, (I_z)_{\text{steady}}$ are assigned by the definition of the lower and upper values of the range of possible values along with the total number of values for that specific variable. The simulation is then performed for each of the n computational elements as well as for each combination of the dynamic input variables.

For each simulation, the number of unstable elements (*failure percentage*) and the corresponding volume of available debris are provided as outputs.

The obtained data are then elaborated, by simple interpolation, in order to build, for each value of antecedent rain $(I_z)_{\mathrm{steady}}$, a graph representing the intensity-duration rainfall curves producing a fixed value of the failure percentage or a fixed value of the total volume of possible debris flow.

2.2 Pressure head response to variation in rainfall duration

The stability conditions consequent to different rainfall events having the same accumulated rainfall (and therefore rainfall intensity decreasing with rainfall duration) has been studied. After substitution into Eq. (4) of $I_z = H/T$, where H is the accumulated rainfall, the time derivative of $\psi(Z,T)$ can be easily obtained for the case of constant H. From the analysis of the sign of the derivative results that the function ψ/Z increases with rainfall duration when the following condition applies:

$$\mathrm{erfc}\frac{1}{\sqrt{T^*}} - 0.5\sqrt{\frac{T^*}{\pi}}\exp\left(\frac{-1}{T^*}\right) > 0 \tag{7}$$

Since this is implicit in the variable T^* it has been solved numerically. It results that the function ψ/Z increases with rainfall duration when:

$$T^* < 5.33 \tag{8}$$

Substituting Eq. (8) into Eq. (6) ψ/Z result to be crescent with rainfall duration when T is lower than a critical value T_{crit} given by:

$$T_{\mathrm{crit}} = 1.4\frac{Z^2}{D_0\cos(\alpha)} \tag{9}$$

In Fig. 1 two examples are reported. The soil parameters and the rainfall characteristics are the same for the two cases except the D_0 that in case (b) is 10 times greater than in case (a). The input data used for these simulations are reported in Table 1. An important consequence of this behaviour is that, in case of small diffusivities, the water pressures continually increase at constant accumulated rainfall with increasing rainfall durations until durations are lower than a rather high T_{crit}. For example, in the case (a) of Fig. 1 $T_{\mathrm{crit}} = 7.2\,\mathrm{h}$.

The expression of T_{crit} given by Eq. (9) is similar to the time scale Z_T^2/D_0 that has been indicated by Iverson (2000) as the minimum time necessary for strong normal slope pore pressure transmission from the ground surface to depth Z_T. This means that the analytic solution of Richards equation (Eq. 4) proposed by Iverson (2000) can correctly estimate only the effects of rainfalls with duration greater than the critical value. On the other hand, the range of rainfall duration that can be simulated is also limited by the another time scale (A/D_0) that expresses the minimum time necessary for strong lateral pore pressure transmission. The ranges of possible rainfall durations are reported in Table 2. for different value of D_0. As a result, when D_0 is lower than $10^{-4}\,\mathrm{m^2\,s^{-1}}$ only the effects of daily rainfall can be assessed by the model.

3 Study case

The Sambuco Basin is a steep coastal watershed of Amalfi Peninsula, Southern Italy (Fig. 2); it covers an area of about $6.4\,\mathrm{km}^2$, with a mean elevation of 422 m a.s.l. and a mean slope of 32°; the main river channel is 4.8 km with a N–S orientation. The area consists of a set of small and steep catchments covered by a series of pyroclastic deposits dating back to the Somma–Vesuvius volcanic eruptions. The area has been affected by extreme weather events with catastrophic consequences (Ciervo et al., 2012; De Luca et al., 2010; Esposito et al., 2003; Papa et al., 2011a). The pyroclastic soils covering the carbonatic rock of the Campanian Appennine are often affected by debris flow events (Cascini et al., 2008; Martino and Papa, 2008).

On 25 October 1954, an extraordinary rainfall event hit the area of the Amalfi Coast and Salerno ($\approx 80\,\mathrm{km}^2$); severe flooding and landslides caused 318 fatalities and large-scale damage (Frosini, 1955). The Sambuco Basin was on the west margin of the affected area. Slope failures mainly occurred on the east side of the basin. The reconstruction of the meteorological event made by the Servizio Idrografico e Mareografico Italiano (SIMI) has provided the map of isohyets. The intersection between the isohyets and the Sambuco Basin shows a daily cumulative rainfall of 321 mm and a maximum hourly intensity of 86.1 mm h^{-1}. The reconstruction of the areas that were mobilized (Papa et al., 2011a), showed that 2.8 % of the total basin area was affected by the detachments (Fig. 3); the total volume of the involved soil mass has been estimated at around 300 000 m^3. This unstable volume formed a mud-flow that flooded the downstream village of Minori with an estimated peak discharge of about of 58 $m^3 s^{-1}$ (Papa et al., 2011a).

Another debris flow event was observed in 2005. Only 0.3 % of the basin area was mobilized (Fig. 3) and the generated debris flow did not reach Minori.

The topographic features ($A/b, \alpha$) of the basin have been derived trough a GIS-based approach over a 5 × 5 m DTM.

The observed correlation between surface geomorphology and spatial variability of soils and deposit was used to derive a map of soils at scale 1 : 2000. The catchment area has been divided into 21 geomorphological homogeneous units (Fig. 4). For each unit the value of soil depth (Z_T) is assigned (Papa et al., 2011a). The soil properties (γ_s, ϕ, c, K_x, K_z) are estimated by literature data (Basile et al., 2003; Bilotta et al., 2005; Ciollaro and Romano, 1995; Iamarino and Terribile, 2008). The input static variables of the Sambuco Basin are reported in Table 3.

The diffusivity D_0 has been estimated through the equation:

$$D_0 = \frac{K_z}{C_0} \tag{10}$$

where C_0 is the change in volumetric water content per unit change in pressure head when the soil is close to saturation. The soil water retention curve have been described by means of the analytical equation proposed by van Genuchten (1980). The parameters of the van Genuchten equation have been estimated for the pyrolclatic soils of

Campanian Appennine (Basile et al., 2003; Ciollaro and Romano, 1995). In the present study, C_0 has been estimated trough the derivative of the van Genuchten equation, using the literature estimates of the parameters. It has been obtained that, when the water retention is equal to 90 % of the saturated water content, $1/C_0$ is approximately equal to 2. As a consequence the value of the characteristics diffusivity has been estimated as $D_0 = 2K_z$.

The resulting values of T_{crit} varies depending on the different values that soil depth and permeability assume in the 21 soil districts. The resulting T_{crit} ranges from few minutes to few days.

4 Results and discussion

The data set, obtained through the numerical model described above, has been elaborated in order to draw intensity-duration curves (ID curves) for any fixed value of the antecedent rain.

Any ID curve corresponds to a fixed value of the ratio between the amounts of unstable computational elements to the total amount of elements (failure percentage).

The simulation results are compared with the ID curve relative to the event that occurred in October 1954 (Fig. 5). The months before that event were dry and therefore the comparison was carried out with the results obtained for the antecedent rain equal to zero. The input static variables are fixed as explained in the above paragraph, except for the soil cohesion that was incremented of 25 %. An higher value of the soil cohesion may be necessary in order to take into account the stabilizing effects of the plant roots and of the eventual stable elements surrounding the instable ones. Both this contributions to soil stability are neglected by the model.

For an event rainfall with a duration of about 6 h, the ID curve of the 1954 event approaches the ID curve corresponding to a failure percentage of 3 %. This result is in good agreement with the observed failure percentage that, as assessed above, was about 2.8. The rainfall duration that result critic for debris flow formation is 6 h; this result is coherent with the timing of the debris flow.

The 2005 event was also studied. This event followed a moderate rainy period, the total rainfall amount of the month before was 212 mm. Neglecting this antecedent rainfall we can compare the ID curve of the event with the same ID curve of Fig. 5. The event rainfall curve approaches the ID lines corresponding to simulated failure percentages of 0.3 %, for rainfall durations of about 8 h. This is in good agreement with the observed failure percentage (0.3 %). After the position of antecedent rain equal to the observed value (212 mm month^{-1}) the only antecedent rain, without any event rain, causes a failure percentage greater than the observed one (Papa et al., 2011b). This result confirms that, as reported in literature (Godt et al., 2008), the hypothesis of steady groundwater flow conditions, used in the simulation of the antecedent rain effects, gives possible overestimation of the failure percentage.

The simulation results have been also compared with a rainfall threshold line, derived through the elaboration of empirical data relative to the pyroclastic deposits of Campania Region (Calcaterra et al., 2000). From the comparison with the simulation results, the threshold line proposed by Calcaterra et al. (2000) corresponds to a failure percentage of about 0.2 % (Fig. 5).

Intensity duration lines obtained by the simulations, may be directly used as a rule for providing DF warnings, once a threshold is fixed for the failure percentage. Such a threshold may be fixed by taking into account that when the instable areas are not wide enough, the mobilized soil is not able to reach the downstream vulnerable areas. When a large number of observed land instabilities is available, the threshold may be fixed by searching for which of the consequent debris flows reached the downstream vulnerable areas. In the studied example, as the 2005 event (failure percentage = 0.3 %) did not reach Minori the critical failure percentage should be fixed between 0.3 % and 3 %. The critical rainfall threshold curves is set equal to the ID curve giving a simulated failure percentage equal to the critical one. Once the CRT curve is fixed the number of false alarms in a playback period can be evaluated. The maximum rainfall intensities, at given durations, observed in the decade 2002–2011 are reported in Fig. 5. If, for example, the RTF was set corresponding to a failure percentage of 1 % no false alarm would have been given in the decade 2002–2011.

When the historical database is not wide enough, or in the case of total absence of historical debris flow events, the failure threshold can be fixed by simulating the downstream effect of different debris flow volumes. These simulations can be performed through the mathematical and numerical modeling of debris flows propagation (O'Brien et al., 1993; Medina et al., 2008). By carrying out a large number of simulations with different input volumes (and consequently discharges), it is possible to asses a threshold for the total amount of debris volume that may comport an hazard for the downstream areas.

Once the volume threshold is fixed, a graph similar to the one shown in Fig. 6 may be used as a rule for DF warnings. In this kind of graph, the simulation results are elaborated in order to show, for any antecedent rain, the intensity duration rainfall curve giving place to a fixed value of the total amount of available debris volume. The ID curve of 1954 event lays between the ID curves corresponding to a total instable volume of 300 000 and 400 000 thus being in good agreement with the estimated total volume of the event.

The sensitivity of the model to changes in the diffusivity (D_0) has been investigated. The same input data of the simulation discussed above (sim01, Fig. 5) are used in a new simulation (sim02). The only difference between the two simulation is the value assigned to D_0 that is respectively $D_0 = 2K_z$ for sim01 and and $D_0 = 0.1K_z$ for sim02. The values of T_{crit} change consequently to changes in D_0, in case of sim01 T_{crit} ranges from few minutes to few days while in case of sim02 it ranges from one hour to one month. In Fig. 7 are compared the results of the two simulations. In this case the accumulated rainfall is reported in the graph instead of the rainfall intensity. Each curve of accumulated rainfall versus rainfall duration correspond to a fixed value of the generated failure percentage. As expected, when D_0 is smaller the basin is more stable. In case of sim01 the considered rainfall durations (from 0 to 24 h) are smaller than T_{crit}

for the major part of the basin and the critical accumulated rainfall curves increase with rainfall duration. On the contrary, in case of sim2, $T < T_{\text{crit}}$ for almost the entire basin, and the critical accumulated rainfall curves decrease with rainfall duration. This result is coherent with the observation made in the above Sect. 2.2. Attention should payed on the values of T_{crit} as the simulations of rainfall durations with $T < T_{\text{crit}}$ give unreasonable results.

5 Conclusions

A simple model has been implemented based on the analytical solution of the Richards equation for the short term, transient piezometric responses to rainfall (Iverson, 2000). The model performs stability simulations for any possible combination of rainfall duration and intensity. These simulations are repeated varying the antecedent rainfall whose effects are computed in the hypothesis of steady state conditions (Montgomery and Dietrich, 1994).

ID curves corresponding to fixed values of failure percentages are drawn through elaboration of simulation results. The simulated ID curves are compared with observed events in a test bed catchment. The stabilizing effects of plant roots and of eventual stable computation element surrounding instable ones are taken into account trough a calibrated increase in soil cohesion.

A critical value of the rainfall duration is analytically derived. Simulation of rainfall duration lower than the critical value give unrealistic results because, in this condition, the water pressure heads increase with rainfall duration at constant accumulated rainfall.

The ID curves obtained through the implemented model can be used as critical rainfall threshold once a critical value of the failure percentage, or a critical value of the total instable volume, is set.

Though its simplicity, the proposed methodology provides critical rainfall thresholds to be used for early warning system. On the contrary of empirically derived threshold, the present methodology can be used also for basin where the database of past event

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

observation is poor and in basin where the soil characteristics have changed for natural or anthropic reasons.

More complex model, based on the solution of the complete Richards equation could overcome some of the drawback of the present approach, as the overestimation of antecedent rainfall impact and the limitations in the duration of the rainfalls that can be simulated. On the other hand the computational time could became too long, for practical applications, because of the great required number of simulations.

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References

Basile, A., Mele, G., and Terribile, F.: Soil hydraulic behaviour of selected benchmark soil involved in the landslide of Sarno 1998, Geoderma, 117, 331–346, 2003.

Bathurst, J. C., Burton, A., Clarke, B. G., and Gallart, F.: Application of the SHETRAN basin-scale, landslide sediment yield model to the Llobregat Basin, Spanish Pyrenees, Hydrol. Process., 20, 3119–3138, 2006.

Beven, K. J. and Kirby, M. J.: A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant, Hydrolog. Sci. Bull., 24, 43–69, 1979.

Bilotta, E., Cascini, L., Foresta, V., and Sorbino, G.: Geo-technical characterisation of pyroclastic soils involved in huge flow-slides, Geotechnical and Geological Engineering, 23, 365–402, 2005.

Brunetti, M. T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D., and Guzzetti, F.: Rainfall thresholds for the possible occurrence of landslides in Italy, Nat. Hazards Earth Syst. Sci., 10, 447–458, doi:10.5194/nhess-10-447-2010, 2010.

Caine, N.: The rainfall intensity–duration control of shallow landslides and debris flows, Geogr. Ann. A, 62, 23–27, 1980.

Calcaterra, D., Parise, M., Palma, B., Pelella, L.: The influence of meteoric events in triggering shallow landslides in pyroclastic deposits of Campania, Italy, in: Proceedings of the 8th International Symposium on Landslides, edited by: Bromhead, E., Dixon, N., and Ibsen, M. L., A. A. Balkema, Cardiff, Wales, 1, 209–214, 2000.

Casadei, M., Dietrich, W. E., and Miller, N. L.: Testing a model for predicting the timing and location of shallow landslide initiation in soil-mantled landscapes, Earth Surf. Proc. Land., 28, 925–950, 2003.

Cascini, L., Ferlisi, S., and Vitolo, E.: Individual and societal risk owing to landslides in the Campania region (Southern Italy), Georisk, 2, 125–140, 2008.

Ciervo, F., Papa, M. N., Medina, V., and Bateman, A.: Ricostruzione e modellazione numerica di un evento di flash flood. Il caso di Atrani 2010, L'acqua, 3, 21–30, 2012.

Ciollaro, G. and Romano, N.: Spatial variability of the hydraulic properties of a volcanic soil, Geoderma, 65, 263–282, 1995.

Crozier, M. J.: Landslides: Causes, Consequences and Environment, Routledge, London, 1989.

De Luca, C., Furcolo, P., Rossi, F., Villani, P., and Vitolo, C.: Extreme Rainfall in the Mediterranean, in: Proc. Int. Conf. International Workshop Advances in Statistical Hydrology, 23–25 May, Abstr. No. 8, Taormina, Italy, available at: http://www.risorseidriche.dica.unict.it/Sito_STAHY2010_web/proceedings.htm (last access: 9 November 2012), 2010.

Esposito, E., Porfido, S., Violante, C., and Alaia, F.: Disaster induced by historical floods in a selected coastal area (Southern Italy), in: Paleofloods, Historical Floods and Climatic Variability: Applications in Flood Risk Assessment, edited by: Thorndycraft, V. R., Benito, G., Barriendos, M., and Llasat, M. C., Proc. Int. Conf. PHEPRA Workshop, Barcelona, 16–19 October, 2002, CSIC – Centro de Ciencias Medio ambientales, Madrid, 143–148, 2003.

Frosini, P.: Il nubifragio di Salerno del 25–26 ottobre 1954, Giornale del Genio Civile, Vol. 93, Ministero dei Lavori Pubblici (Istituto Poligrafico dello Stato), 1955.

Godt, J. W., Baum, R. L., Savage, W. Z., Salciarini, D., Schulz, W. H., Harp, E. L., and Richard, U: Transient deterministic shallow landslide modeling: requirements for susceptibility and hazard assessments in a GIS frame work, Eng. Geol., 102, 214–226, 2008.

Iamarino, M. and Terribile, F.: The relevance of andic soils in mountain ecosystems in Italy: a pedological investigation, Eur. J. Soil Sci., 59, 1284–1292, 2008.

Iverson, M.: Landslide triggering by rain infiltration, Water Resour. Res., 36, 1897–1910, 2000.

Iverson, R. M., Reid, M. E., and LaHusen, R. G.: Debris flow mobilization from landslides, Annu. Rev. Earth Pl. Sc., 25, 85–138, 1997.

Lehmann, P. and Or, D.: Hydromechanical triggering of landslides: from progressive local failures to mass release, Water Resour. Res., 48, W03535, doi:10.1029/2011WR010947, 2012.

Martino, R. and Papa, M. N.: Variable-concentration and boundary effects on debris flow discharge predictions, J. Hydraul. Eng., 134, 1294–1301, doi:10.1061/(ASCE)0733-9429(2008)134:9(1294), 2008.

Medina, V., Bateman, A., and Hürlimann, M.: FLAT-Model: a 2-D finite volume code for debris-flow modeling, application to events occurred in the Eastern Pyrenees, Int. J. Sediment Res., 23, 348–360, 2008.

Montgomery, D. R. and Dietrich, W. E.: A physically-based model for topographic control on shallow landsliding, Water Resour. Res., 30, 1153–1171, 1994.

O'Brien, J. S., Julien, P. Y., and Fullerton, W. T.: Two-dimensional water flood and mudflow simulation, J. Hydraul. Eng., 119, 244–261, 1993.

Papa, M. N., Trentini, G., Carbone, A., and Gallo, A.: An integrated approach for debris flow hazard assessment – a case study on the Amalfi Coast – Campania, Italy, in: Proc. Int. Conf. DFHM 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, 14–17 June 2011, University of Padua, Italy, 983–992, doi:10.4408/IJEGE.2011-03.B-107, 2011a.

Papa, M. N., Medina, V., and Bateman, A.: Derivation of critical rainfall thresholds for debris flow warnings through mathematical and numerical modeling, 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, 14–17 June 2011, University of Padua, Italy, 495–502, doi:10.4408/IJEGE.2011-03.B-055, 2011b.

Simoni, S., Zanotti, F., Bertoldi, G., and Rigon, R.: Modeling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS, Hydrol. Process., 22, 532–545, 2008.

Taylor, D. W.: Fundamentals of Soil Mechanics, Wiley, New York, 1948.

Wieczorek, G. F. and Glade, T.: Climatic factors influencing occurrence of debris flows, in: Debris-Flow Hazards and Related Phenomena, Praxis, edited by: Jakob, M. and Hungr, O., Springer, Chichester, UK, Ch. 14, 325–362, 2005.

van Genuchten, M. T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892–898, 1980.

Table 1. Soil parameters, slope degree and initial condition used to generate Fig. 1.

Z_T m	γ_s $\mathrm{kg\,m^{-3}}$	ϕ °	c Pa	K_z $\mathrm{mm\,s^{-1}}$	α $\mathrm{mm\,s^{-1}}$	d_z m
1	1450	35	1	6×10^{-5}	26.6	1

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 2. Time scales of pore pressures transmission in response to rainfall, assuming $Z_T \sim 1$ m and $A \sim 100\,\mathrm{m}^2$.

D_0 $\mathrm{m}^2\,\mathrm{s}^{-1}$	Minimum rainfall duration Z_T^2/D_0 –	Maximum rainfall duration A/D_0 –
10^{-6}	12 days	3 yr
10^{-5}	1 day	116 days
10^{-4}	3 h	12 days
10^{-3}	17 min	13 h

Table 3. Values of the static variables for the 21 homogeneous district of Sambuco Basin.

districts –	Z_T m	γ_s $\mathrm{kg\,m^{-3}}$	ϕ °	c kPa	K_x $\mathrm{mm\,s^{-1}}$	K_z $\mathrm{mm\,s^{-1}}$
1	0.5	1500	32	10	0.96	0.96
2	0.5	1400	35	5	0.36	0.06
3	0.5	1400	35	5	0.36	0.06
4	1	1400	35	5	0.36	0.06
5	1.5	1400	35	5	0.36	0.06
6	1	1400	35	5	0.36	0.06
7	1.5	1400	35	5	0.36	0.06
8	2	1400	35	5	0.36	0.06
9	5	1400	35	5	0.36	0.06
10	1	1500	32	10	0.22	0.11
11	1.5	1500	32	10	0.22	0.11
12	2	1500	32	10	0.22	0.11
13	3.5	1500	32	10	0.22	0.11
14	5	1500	32	10	0.22	0.11
15	1	1800	35	0	0.68	0.68
16	1.5	1800	35	0	0.68	0.68
17	3.5	1800	35	0	0.68	0.68
18	5	1800	35	0	0.68	0.68
19	4.5	1500	32	10	0.18	0.10
20	5	1800	35	0	0.68	0.68
21	4	1500	32	10	0.09	0.09

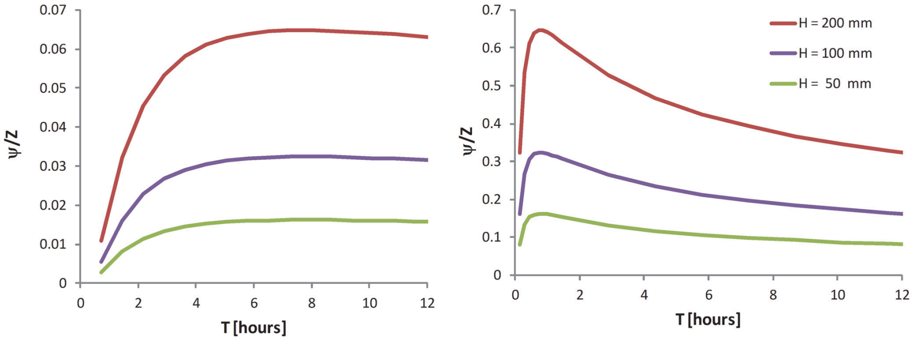

Fig. 1. Ratio between pressure head and soil depth versus rainfall duration at constant cumulative rainfalls (H). Input data of the simulations are reported in Table 1. **(a)** $D_0 = 6 \times 10^{-5}\ \mathrm{m}^2\ \mathrm{s}^{-1}$; **(b)** $D_0 = 6 \times 10^{-4}\ \mathrm{m}^2\ \mathrm{s}^{-1}$.

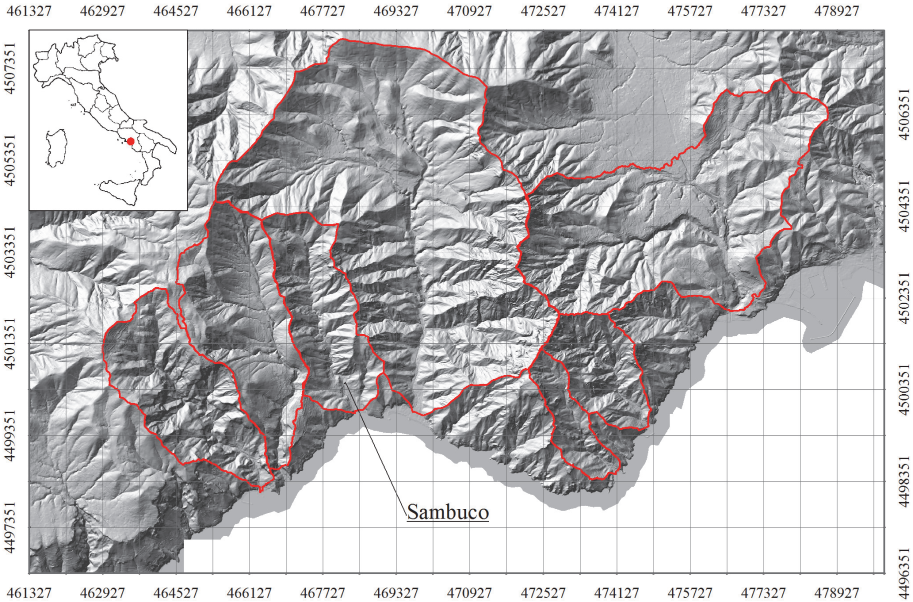

Fig. 2. Geographical context of the study area (WGS 1984, UTM Zone 33° N).

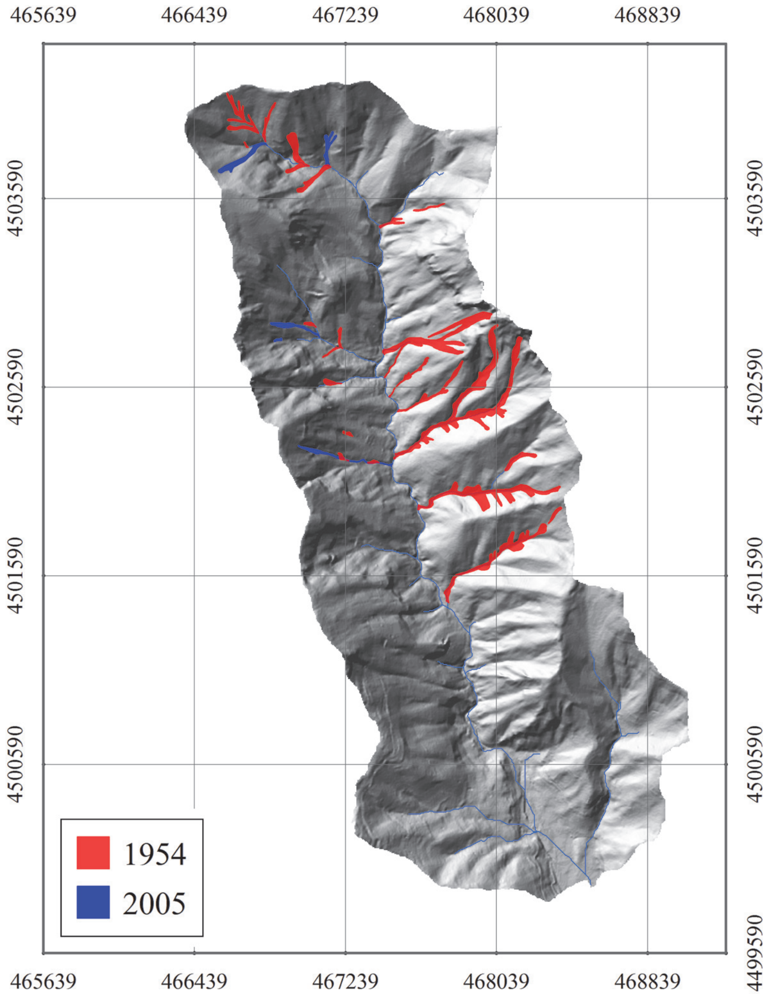

Fig. 3. Traces of the landslides occurred in 1954 and 2005 events (Papa et al., 2011a).

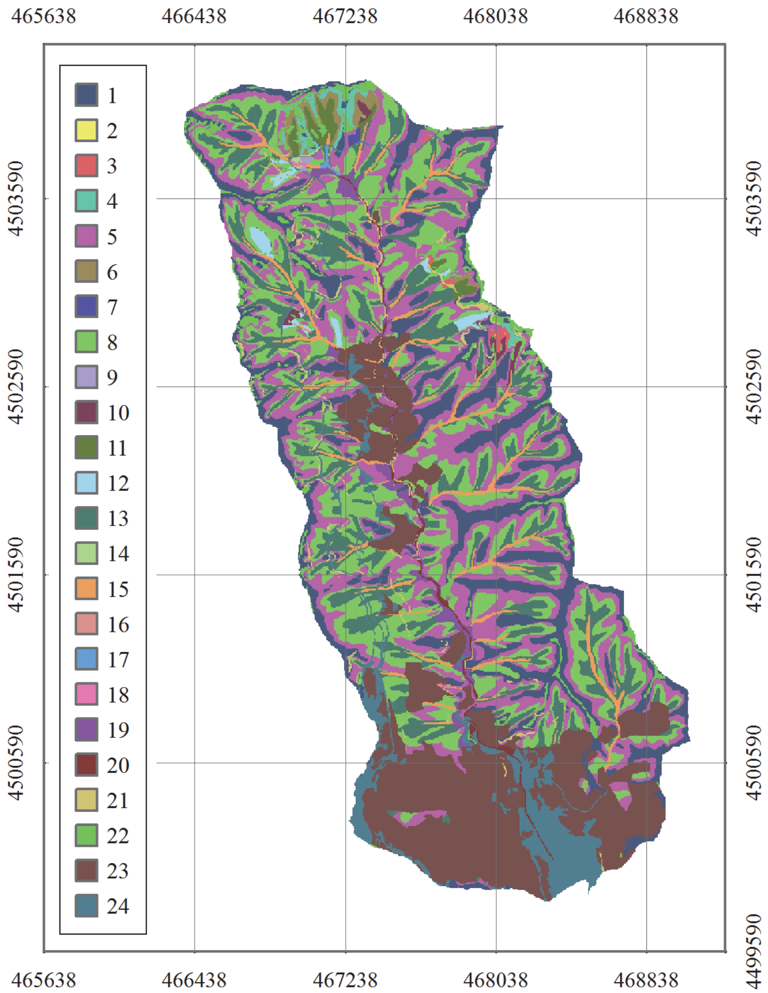

Fig. 4. Map of the geomorphological homogeneous units (Papa et al., 2011a).

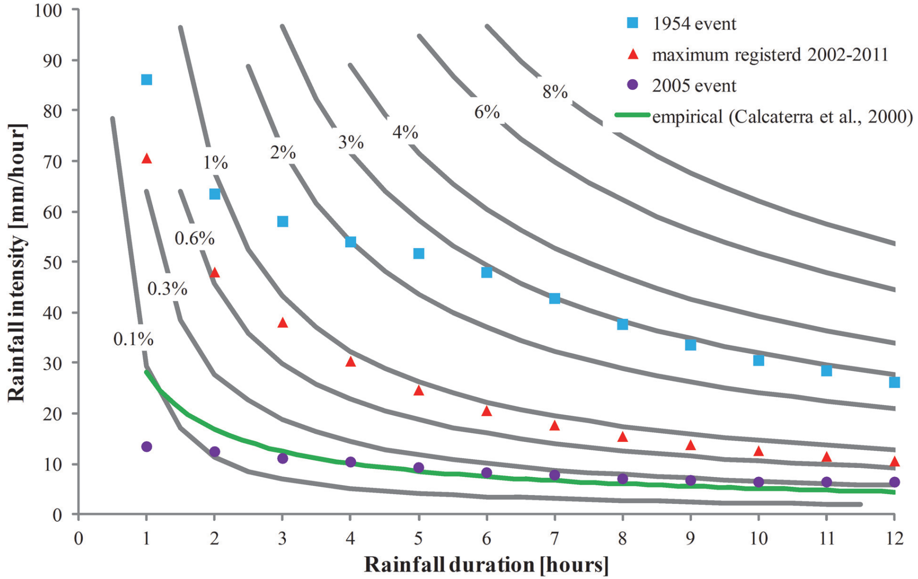

Fig. 5. Comparison between registered rainfalls and simulated ID curves at fixed values of the failure percentage.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

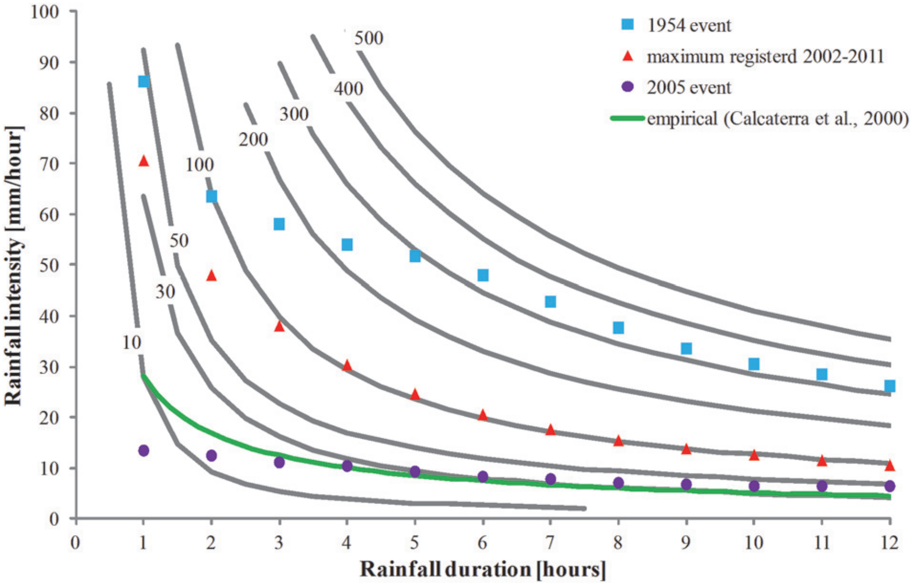

Fig. 6. Comparison between registered rainfalls and simulated ID curves at fixed values of total instable volumes (thousands of m^3).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

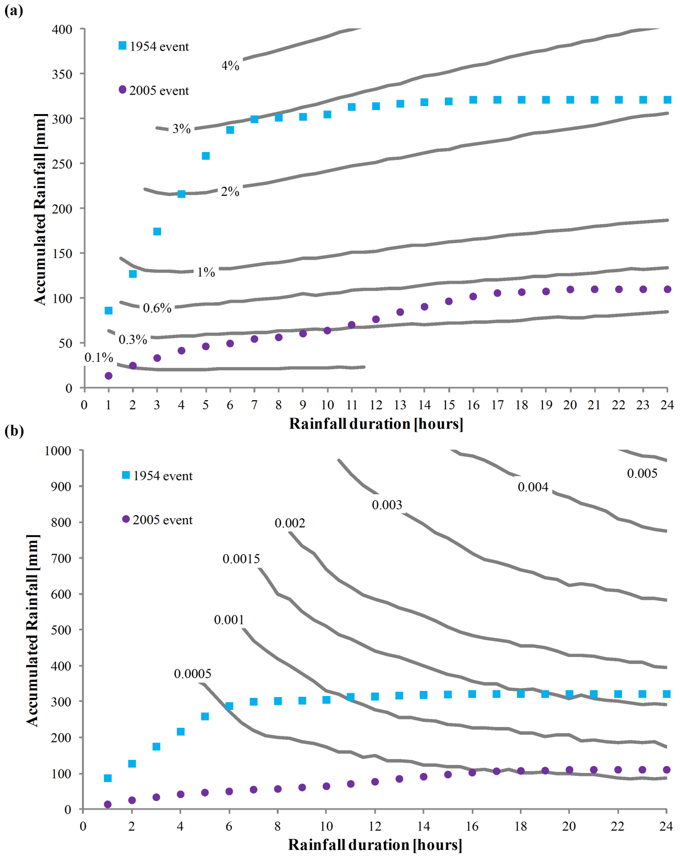

Fig. 7. Accumulated rainfall versus rainfall duration at fixed values of the failure percentage: **(a)** sim01 with $D_0 = 2K_z$; **(b)** sim02 with $D_0 = 0.1K_z$.