HYDROLOGIC CONDITIONS LEADING TO DEBRIS-FLOW INITIATION IN THE CAMPANIAN VOLCANOCLASTIC SOILS

G. B. Chirico[a], P. Claps[b], F. Rossi[a] & P. Villani[c]

[a] *DIC, Univ. of Salerno, Via P. D. Melillo, 84084 Fisciano (SA), Italy;*
[b] *DIFA, Univ. of Basilicata, V.le della Tecnica, 30, 85100, Potenza, Italy;*
[c] *DIC, Univ. of Parma, Parco delle Scienze, 181/A, 43100 Parma, Italy.*

ABSTRACT

The debris flows in the volcanoclastic soils mantling the Tyrrhenian side of the Campanian carbonatic ridges represent a significant natural hazard for the intense urbanized areas lying at the toe. Hazard mitigation planning requires the knowledge of the hydrologic conditions triggering debris flows. The hydrologic response of the landscapes is various and complex, depending on the characteristics of the rainstorms and on the hydrologic states of the soil mantle and the limestone bedrock. In the area under study critical events occurred associated either with extraordinary extreme rainfall or with ordinary extreme rainfall at the end of rainy season. Extraordinary extreme rainfall can trigger debris flows by lateral surface and subsurface flow. At the end of the wet season debris flows can be triggered by ordinary extreme rainfall, that produces water out-flows from the bedrock at higher elevation. Both the soil mantle and the limestone bedrock have a nonlinear behavior all over the hydrological year. The soil mantle presents two dominant states, a wet state and a dry state; the limestone bedrock has three different characteristic responses. A statistical hydrological analysis of the event of the May 1998 seems to confirm this physical interpretation. A conceptual model has been developed to simulate critical hydrologic conditions leading to debris flow initiation. With lack of field data and poor historical information availability, a conceptual approach compared with an empirical or a statistical one, permits to drive the model calibration on the basis of the physical meaning of parameters. The proposed model has two nonlinear components, representing the response of the soil mantle and of the limestone bedrock. First results are tested with reference to historical events occurred in the Campania Region.

1. INTRODUCTION

Debris flows originating from soil slips are not uncommon on the western side of the Campanian Apennines, in Southern Italy. Single debris flow occurs every 2-5 years within the whole area. Catastrophic simultaneous debris flows occur less frequently, about every 40 years. Debris flows are triggered usually by extraordinary extreme rainfall; but, at the end of the rainy season, from February to May, even ordinary extreme rainfall can originate debris flows.

Owing to extensive and uncontrolled urbanization in the last fifty years, in which settlements were built up at toe of the ridges, on the ancient soil deposits, debris flows represent the main hydrogeological risk in Campania Region.

The 5th of May 1998, during a 30 hours rainfall event, with an average intensity of 3-4 mm/h, more than 140 soil slips occurred around the ridge of Pizzo d'Alvano, about 40 km east of Naples. Most all of these soil slips originated debris flows, producing deaths and damages in the towns of Sarno, Quindici, Siano and Bracigliano.

To simulate the hydrological conditions leading to initiation debris flow, a conceptual hydrological model has been developed. The model is based on a physical interpretation of the hydrologic processes leading to excess in water content of soil and bedrock, to evaluate their influence on historical shallow landslides occurred on the western side of the Campanian Apennines.

2. UPSLOPE HYDROLOGIC RESPONSE OF PYROCLASTIC SOIL MANTLED LIMESTONE RIDGES

The Campanian Apennines are carbonate ridges mantled by pyroclastic materials, deriving from Vesuvius volcanic activity in the last 22.000 years. The observed debris flows in this area are usually originated from shallow landslides in the pyroclastic mantle, triggered upslope the first order channel, within the morphological concavity called "zero-order basin". Both lateral subsurface flow in the pyroclastic mantle and occasional water outflows from the limestone bedrock have a basic rule in these failures.

Therefore, the comprehension of the upslope hydrologic response and, in particular, the mutual interaction between pyroclastic mantle and limestone bedrock is fundamental to develop a mathematical model that can simulate the hydrological condition leading to debris flows initiation.

2.1 Dominant processes in the spatial moisture distribution in the pyroclastic mantle

The undisturbed pyroclastic mantle consists of layers of ash, pumice and paleosoil. Its thickness varies along the landscapes, from tens of meters at the bottom to less than one meter at the top.

Laboratory tests made on samples taken in the Campanian plain show that hydraulic conductivity of ash soils has nonlinear dependence on water content: a 50% reduction of in relative saturation corresponds to a reduction of the hydraulic conductivity of more than an order of magnitude (Romano, 1990). This nonlinear behavior is amplified in the pumice, which can be classified as sand/gravel.

During dry periods, when evapotranspiration exceeds rainfall, the moisture distribution is dominated by vertical fluxes of evapotranspiration and infiltration. The lateral hydraulic conductivity is nearly zero, due to the low water content. The water content is controlled by the local properties of the soil, by vegetation and, on larger space scale, by solar radiation and spatial distribution of rainfall.

During wet periods, the lateral subsurface and surface flows become the dominant processes in moisture distribution. The areas of high local convergence, at the closing section of the "zero-order basin", are the firsts that become wet. The local water content depends on the upslope contributing area.

The dry-wet transition is more or less fast depending on the local rainfall regime and on the soil hydraulic conductivity and retention curves (Grayson, 1997).

2.2 Hydrologic response of the limestone bedrock

In the study area the bedrock is variably fractured by tectonic activity; it is more fractured and altered by weathering phenomena near the surface. Well tests proved that the hydraulic conductivity of the carbonate bodies decrease considerably in the first 10-15 meters. Due to the discontinuity of the hydraulic conductivity, a perched water table sets up within the weathered layer. Recorded water outflows after rainfalls even at high elevation represent proves of the presence of this perched water table (Rutigliano, 1999; Cascini at al., 1999).

The structural joints within the bedrock have a basic role in the evolution of the underground drainage system and on bedrock surface morphology. Perennial springs and occasional water outflows from the bedrock are often located in the intersection points of structural joints (Cascini et al., 1999).

The "zero-order basin" corresponds to the upper limestone structural element, in which the effects of near-surface weathering phenomena are more developed. The closure section of the "zero-order catchment" represents the preferential convergence point of the lateral surface and subsurface flow and the site of seasonal water outflows from the perched water table (Cascini et al., 1999).

It is possible to distinguish three dominant responses of the extremely fractured near-surface bedrock:

1. Recharge toward the base groundwater;
2. Intermediate water outflow;
3. Higher water outflow.

The recharging phase starts at beginning of the rainy season. During this phase a perched water table sets up in the extremely fractured bedrock layer. In the second phase, starting from the middle of the rainy season, water outflows appear at high elevation, usually at the head of first order channels, during and after rainfalls. The third phase is occasional: at the end of the rainy season, when the perched water table has reached the maximum level, heavy rainfall can produce temporary water outflows at highest elevation, within "the zero-order basins".

3. Hydrologic conditions leading to debris-flow initiation: the event of May 1998

3.1 Description of the event

A hydrological analysis of Campanian historical events showed that debris flows originated from soil slips were triggered by prolonged rainfall (Rossi and Chirico, 1998).

Soil slips are triggered by lateral subsurface and surface storm flow, produced by landscape response to extraordinary extreme rainfall, and happen more frequently in the rainy season. At the end of the rainy season, when the perched water table in the fractured bedrock reaches the maximum level, soil slips can be triggered even by ordinary extreme rainfall, that produce simultaneously subsurface flow and occasional water outflows from the bedrock.

The hydrologic conditions that produced the catastrophic event of the 4-5th of May 1998 in Sarno fall in the second case. Fig. 1 shows the return periods of the rainfalls during the catastrophic event, registered at the Sarno raingauge: the maximum estimated return period is 5 years for a duration of 24 hours. The Sarno raingauge, lying at the toe of the Pizzo d'Alvano ridge (highest elevation at 1133 m a.s.l.) under-estimates precipitation falling uphill. However, on the basis of the spatial analysis of the rainfall event of the 4-5th of May 1998, the maximum estimated return period at Sarno is less than 25 years, for duration of 24-48 hours. These frequencies are incompatible with the extent of that hydrogeological disaster.

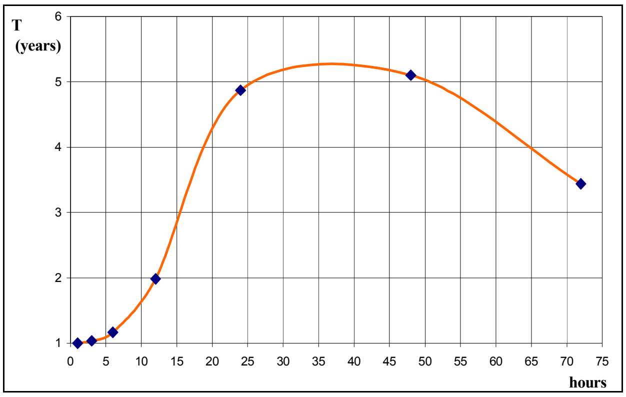

Figure 1. Estimated return periods of the rainfall event of the 3rd-5th of May 1998, recorded at Sarno raingauge.

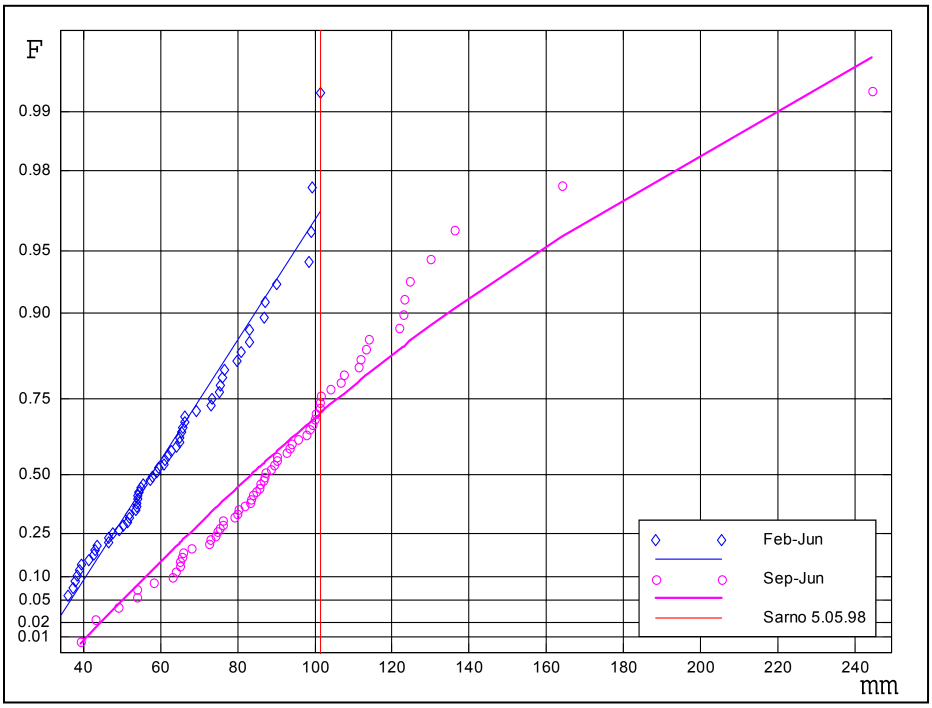

Figure 2: Cumulative distribution functions of the maximum 3-days rainfall within the periods from September to June and February to June (Gumbel probability paper).

Fig. 2 shows the frequency distribution curves of the maximum three days rainfall for the periods: from September to June and February to June. It shows that the rainfall recorded at the Sarno raingauge in the three days of the cited event is greater than the maximum recorded historical value within the period from February to June.
This result confirms that the debris-flow initiation of May 1998 was due to the hydrologic response of a system, such as the fractured bedrock, that is conditioned by long-term antecedent rainfall.

3.2. Rainfall thresholds for debris flows originating from soils slips

Relationships between rainfall and debris flows originating from soil slips have been widely studied to identify threshold values for rainfalls or for other related indexes. Cannon and Ellen (1985), proceeding from a work of Caine (1980) based on worldwide debris flow events, developed intensity-duration thresholds for the San Francisco Bay area. Differently from Caine, they considered the mean annual precipitation (Pma) and divided the San Francisco Bay area in two regions, corresponding to high and low Pma. For each of these regions they proposed an intensity-duration threshold for "abundant" debris flows in this area.
Subsequently Wieczoreck (1987) developed an intensity-duration threshold for La Honda, California, based on an 8-year record of rainfall intensity and duration characteristics leading to debris flow initiations.
The proposed intensity-duration threshold curves present a large variability, depending strongly on the hydrologic conditions of the specific sites and on the characteristics of the considered events. Bounding all the physical processes involved in soil drainage and moisture redistribution in a "black box", these curves cannot simulate the actual prestorm landscape hydrologic conditions.
Wilson and Wieczoreck (1995) proposed a conceptual model called "the leaky barrel model" to simulate the interactions between rainfall and shallow-hillslope pore pressure. The model is mainly based on Campbell's physical hypothesis of debris flows initiation in California (1975). Comparing model simulations with in-site piezometer fluctuations related to rainstorms that triggered or failed to trigger debris flows, the authors defined the model parameters and the critical threshold response representative of the most susceptible slopes in La Honda.
After the May 1998 disaster, rainfall thresholds were defined to protect the settlements at the toe of the Pizzo d'Alvano ridge from the residual risk (Rossi and Chirico, 1998). These thresholds have been defined analyzing the relationships between daily rainfall and debris flow events in the whole Campania Region.
The diagram in fig. 3 shows two-day rainfalls that triggered debris-flows versus the cumulative antecedent rainfall computed from the beginning of the rainy season, and the related lower envelope curve. In the same diagram, two-day

rainfall events that failed to trigger debris flows are plotted with the related upper envelope curve. The distance between the two envelope curves represents the uncertainty with respect to the use of the lower envelope as a rainfall threshold.
Afterwards, the FLaIR (Versace et al., 1998) model was applied to some debris flows events in Campania. The model was originally developed to simulate and forecast deep landslide movements activated by rainfall (Sirangelo et al, 1996). A linear model, characterized by an impulse response function called "filter function", reproduces the relation between rainfall and the hydrologic response causing landslide movements (i.e. the water table excursions). The model response is defined by a simple function, called "mobility function", obtained by convolution of the rainfall with the "filter function". The triggering threshold is defined by the minimum values attained the "mobility function" in correspondence of landslide movements.

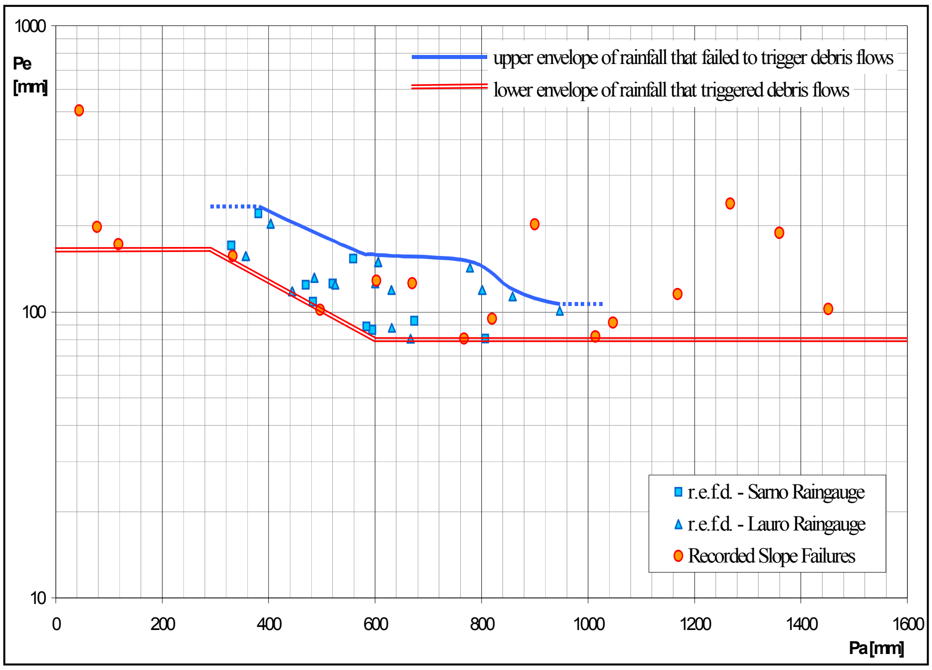

Figure 3. Two-day rainfall (Pe) plotted versus seasonal antecedent rainfall (Pa). Comparison between rainfall events that triggered debris flows and rainfall events that failed to trigger debris flow (r.e.f.d.).

4. A CONCEPTUAL MODEL OF HYDROLOGICAL DEBRIS FLOW INITIATION

A model for conceptual simulation of the upslope hydrologic response of the limestone ridges is proposed in this paper.
The control volume of the model is the “zero-order basin”, formed by the pyroclastic mantle and the extremely fractured near-surface bedrock, where the perched water table sets up and where the soil slips that originate debris flows take place. The input is the rainfall (P); the outputs are the evapotranspiration (ET), the lateral surface and subsurface flow, the deep drainage through the base groundwater, the seasonal and the occasional water outflows (see fig. 4).

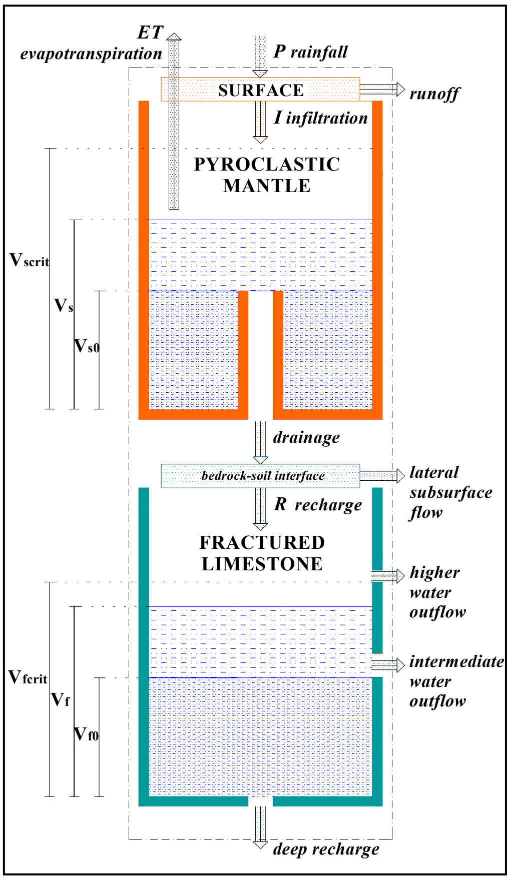

Figure 4. Structure of the proposed conceptual model.

The pyroclastic mantle is represented as a linear tank with a discontinuity representative of the dry-wet state transition. The drainage from the soil mantle is assumed proportional to the amount of retained water (V_s) above a threshold value ($V_{s,0}$), according to a time-response proportionality constant (k_s).

The change in the amount of retained water V_s in the mantle is expressed by the following equations:

$$\frac{dV_s}{dt} = I - ET \qquad V_s \le V_{s,0} \tag{1}$$

$$\frac{dV_s}{dt} + \frac{1}{k_s}\left(V_s - V_{s,0}\right) = I - ET \qquad V_s > V_{s,0} \tag{2}$$

Infiltration rate (I) is assumed proportional to rainfall, by means of a parameter (ψ_I) that varies with the amount of retained water exceeding the threshold $V_{s,0}$:

$$I = \psi_I \cdot P \tag{3}$$

$$\psi_I = \psi_0 \, exp\left[-\frac{max\left(V_s - V_{s,0};0\right)}{\theta}\right] \tag{4}$$

The actual evapotranspiration (ET) is evaluated comparing the soil water content with potential evapotranspiration:

$$ET = min\left(ET_p, V_s\right) \tag{5}$$

The recharge (R) toward the fractured bedrock is assumed to be a fraction of the total drainage from the soil mantle:

$$R = \alpha \cdot \frac{1}{k_s} max\left(V_s - V_{s,0};0\right) \tag{6}$$

The fractured bedrock is also represented as linear tank with a discontinuity that in this case represents the water table threshold above which the intermediate water outflow starts. Drainage toward the base groundwater is assumed proportional to the water table height (V_f), through the constant k_{f1}, while the seasonal water outflow is proportional to the water table height above the threshold $V_{f,0}$, (V_f), through the constant k_{f2}. Constants k_{f1} and k_{f2}

represent the time-response characteristics of the base drainage and the seasonal outflow.
Water table head within the fractured bedrock depends on the recharge by means of the following equations:

$$\frac{dV_f}{dt} + \frac{1}{k_{f1}} V_f = R \qquad V_f \le V_{f,o} \tag{7}$$

$$\frac{dV_f}{dt} + \frac{1}{k_{f1}} V_f + \frac{1}{k_{f2}} \left(V_f - V_{f,0} \right) = R \qquad V_f > V_{f,o} \tag{8}$$

The model is represented overall by the following equations:

$$ET_j = min\left(ET_{p,j}, V_{s,j} \right) \tag{9}$$

$$I_j = \psi_0 \, exp\left[-\frac{max\left(V_{s,j} - V_{s,0}; 0 \right)}{\theta} \right] P_j \tag{10}$$

$$V_{s,j+1} = V_{s,j} + I_j - ET_j \qquad V_{s,j} \le V_{s,o} \tag{11}$$

$$\begin{aligned} V_{s,j+1} = {} & V_{s,0} + \left(V_{s,j} - V_{s,0} \right) exp\left(-\frac{\Delta t}{k_s} \right) + \\ & \frac{k_s}{\Delta t} \left(I_j - ET_j \right) \left[1 - exp\left(-\frac{\Delta t}{k_s} \right) \right] \end{aligned} \qquad V_{s,j} > V_{s,o} \tag{12}$$

$$R_j = \alpha \cdot \left[I_j - ET_j - \left(V_{s,j+1} - V_{s,o} \right) \right] \tag{13}$$

$$\begin{aligned} V_{f,j+1} = {} & V_{f,j} \, exp\left(\frac{-\Delta t}{k_{f1}} \right) + \\ & + \frac{k_{f1}}{\Delta t} R_j \left[1 - exp\left(\frac{-\Delta t}{k_{f1}} \right) \right] \end{aligned} \qquad V_{f,j} \le V_{f,o} \tag{14}$$

$$V_{f,j+1} = V_{f,j}\, exp\left[-\Delta t\left(\frac{1}{k_{f1}}+\frac{1}{k_{f2}}\right)\right] + \frac{1}{\Delta t}\frac{k_{f1}k_{f2}}{k_{f1}+k_{f2}} \cdot \left(R_j + \frac{V_{f,0}}{k_{f2}}\right)\left\{1 - exp\left[-\Delta t\left(\frac{1}{k_{f1}}+\frac{1}{k_{f2}}\right)\right]\right\} \qquad V_{f,j} > V_{f,o} \tag{15}$$

Volume quantities $V_{s,j}$ and $V_{f,j}$ represent the water contents at time-step $j\Delta t$, while the other flux quantities $(\cdot)_j$ represent discrete flux volumes from $j\Delta t$ to $(j+1)\Delta t$.

With respect to other empirical or statistical approaches, the great advantage of using a conceptual model is that model parameters estimation and validation is easier because of their physical meanings. In addition to the time of occurrence of historical events, other data from field monitoring, such as discharge or pore pressures surveys, can be usefully incorporated in the model as input and output data.

According to the described physical interpretation of the hydrologic condition leading to debris flows initiation, two triggering thresholds should be defined within the conceptual model:

a) $V_{s,crit}$, representing the critical value of the retained water into the pyroclastic mantle;
b) $V_{f,crit}$, representing the critical elevation of the perched water table;

The first parameter represents the hydrologic condition that occurs with high-intensity prolonged rainfall, while the second one is associated with prolonged low-intensity rainfall at the end of the rainy season.

4.1 Preliminary application to some historical events

A preliminary application of the model was done with regard to historical events occurred at Sarno.

Due to the lack of field monitoring data, parameter calibration has been done only on the basis of temporal occurrence of the historical events, using the ranking technique (Sirangelo et al., 1996). It consists in the identification of an admissibility field Ω_ϑ for the set of parameters ϑ. This admissibility field is bounded by evaluating the retained water contents, V_s and V_f, on all the range of variability of the parameters and selecting those values that lead at least one of the triggering quantities (V_s and V_f) to assume the k highest values in correspondence of the k historical debris flow events.

For a single event occurred at $j\Delta t$, a set of parameters $\hat{\vartheta}$ is admissible if one of the following conditions is verified:

$$V_s\left(j_1 \Delta t ; \vartheta\right) = \max_{j=1,2,\ldots} \left[V_s\left(j \Delta t ; \hat{\vartheta}\right)\right] \tag{15}$$

$$V_f\left(j_1 \Delta t ; \hat{\vartheta}\right) = \max_{j=1,2,\ldots} \left[V_f\left(j \Delta t ; \hat{\vartheta}\right)\right] \tag{16}$$

The first condition should be verified for debris flow events triggered by prolonged high-intensity rainfall, while the second one refers to debris flow events triggered by prolonged low-intensity rainfalls at the end of the rainy season.

Table 1 synthesizes preliminary results obtained using the ranking technique on some historical events in Campania, presenting for each model component the range of variability of the related parameters. In this analysis, surface runoff and the rate of drainage that produces lateral subsurface flow are neglected. More detailed hydrologic information on the historical events and field data are needed to reduce the model parameter uncertainty.

Pyroclastic mantle	drainage time-response constant (days)	$0.2 < k_s < 1$
	drainage threshold value (mm)	$140 < V_{s,0} < 220$
Fractured bedrock	deep recharge time-response constant (days)	$110 < k_{f,1} < 160$
	seasonal water outflow time-response constant (days)	$1.2 < k_{f,2} < 3$
	seasonal water outflow threshold value (mm)	$120 < V_{f,0} < 170$

Table 1. Preliminary estimate of the range of variability of model parameters using the ranking thecnique.

REFERENCES

Caine N., The rainfall intensity-duration control of shallow landslides and debris flows, *Geografiska Annaler*, 1980, Vol. 62A, pp. 23-27.

Campbell R.H., Soils slips, debris flows and rainstorms in the Santa Monica Mountains and vicinity, southern California, *United States Geological Survey*, Professional Paper 851, 1975.

Cannon S.H. and Ellen S., Rainfall conditions for abundant debris avalanches, San Francisco Bay, California, *California Geology*, 1985, **38**(12), 267-272.

Cascini L., Guida D., Romanzi G., Nocera N. and Sorbino G., A preliminary model for the landslides of May 1998 in Campania Region, *Special Lecture, II International Conference "Geotechinics of Hard Soil – Soft Rock",* vol. III

Grayson R.B., Western A.W. and Chiew F.H.S., Preferred states in spatial soil moisture patterns: local and nonlocal controls, *Water Resources Research*, 1997, vol. 33, no. 12, pp. 2897-2908.

Rossi F. and Chirico G.B., Definizione delle soglie pluviometriche di allarme, *Rapporto Unità Operativa 2.38, C.N.R.-G.N.D.C.I.*, Salerno, Italy, 1998.

Rutigliano R., Modello d'innesco delle colate di fango in un bacino pilota del Pizzo d'Alvano, *Università di Salerno, Tesi di Laurea in Geotecnica*, Salerno, Italy, 1999.

Romano N., Variabilità spaziale delle proprietà idrauliche di un suolo vesuviano, *XXII Convegno di Idraulica e Costruzioni Idrauliche*, Cosenza, Italy, 1990

Sirangelo B. and Versace P., A real time forecasting for landslides triggered by rainfall, *Meccanica*, 1996, 31, 1-13.

Versace P., Sirangelo B. and Chirico G.B., Analisi dell'innesco pluviometrico dell'evento di Sarno del 5 Maggio 1998, *pubblicazione n. 1925, C.N.R.-G.N.D.C.I.*, Salerno, Italy, 1998.

Wieczoreck G.F., Effect of Rainfall intensity and duration on debris flows in Central Santa Cruz Mountains, California, in Costa J.E. and Wieczoreck G.F. (editors), *Debris Flows/Avalanches: Process, Recognition and Mitigation*: Reviews in Engineering Geology, 1987, vol. 7, Geological Society of America, Boulder, Co, pp. 23-104.

Wilson R.C. and Wieczoreck G.F., Rainfall thresholds for the initiation of debris flows at La Honda, California, *Environmental & Engineering Geoscience*, 1995, Vol. 1, No. 1, pp. 11-27.