Rainfall and Senerchia Landslides, Southern Italy

Precipitaciones y Deslizamientos en Senerchia, Sur de Italia

M. Polemio
Istituto di Geologia Applicata e Geotecnia, Facoltà di Ingegneria, Politecnico di Bari, Italy

ABSTRACT: The aim of this work is to highlight the influence exerted by meteoric events on landslide triggering. Taking into account the main geomorphological and hydrogeological features of the mass movements, simple hydrological/statistical methods are suggested. Cumulative daily rainfalls over 1 to 180 days are studied to determine probability distribution functions. Hence the critical rainfall period is determined for a specific landslide and the return period of the hydrological event associated with the landslide is quantified.

RESUMEN: El objetivo de este trabajo es poner en evidencia la influencia ejercida por los episodios meteóricos en el desencadenar la aparición de deslizamientos. Teniendo en cuenta los principales rasgos geomorfológicos e hidrogeológicos de los movimientos de masas, se pueden sugerir métodos hidrogelogico-estadísticos simples. Las precipitaciones diarias acumuladas, que comprenden períodos de 1 a 180 días, serán estudiadas con objeto de determinar las funciones de distribución probabilística. Así, el período de precipitación crítico puede ser determinado para un específico caso de deslizamiento y del mismo modo, el período de "repetición" de un episodio hidrogeológico asociado al deslizamiento puede ser también cuantificado.

1. INTRODUCTION

The study area is located in Southern Italy, south-east of Naples (Figure 1). Phenomena of slope instability and floods have long been a constant feature in this portion of the Apennines, with earthquakes and meteoric events representing the main triggering factors. Landslides have often resulted in dreadful economic and human losses.

This work examines the rainfall/landslide relations for selected events in the upper Sele valley (Figure 1), in the Senerchia area. The purpose of the study is to define the impact of rainfall events on selected landslides. At present, the area is being investigated to identify the spatial trend of environmental variables related to landslides; a site with an active landslide best suited for this research project has been selected.

A number of geological, geomorphological, hydrological and geotechnical features briefly summarised in this paper are examined in detail in the final technical report drawn up under the co-ordination of Prof. Cotecchia (EEC 1996).

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The outcropping lithofacies can be divided into four types (Figure 1).

1) The limestones and dolomitic limestones (Trias-Cretaceous) which constitute the relief.

2) Clayey-marly and clayey-marly-arenaceous flysch, shales, marls, chert limestones, sandstones and varicoloured clays (Upper Cretaceous - Paleocene). The flysch shows a marked heterogeneity and anisotropy

induced by a long geological and tectonic history. Due to their peculiar mechanical and geotechnical behaviour, these successions are highly susceptible to macroscopic slope deformation and mass movement in general (Parise et al. 1997). The flysch is composed essentially of clays and marls. Pelitic fractions are found along with a granular component enriched by chaotic and non - homogeneous pebbles and calcareous blocks.

3) The detrital and breccia deposits of rockfall or scree (Quaternary) have a carbonate

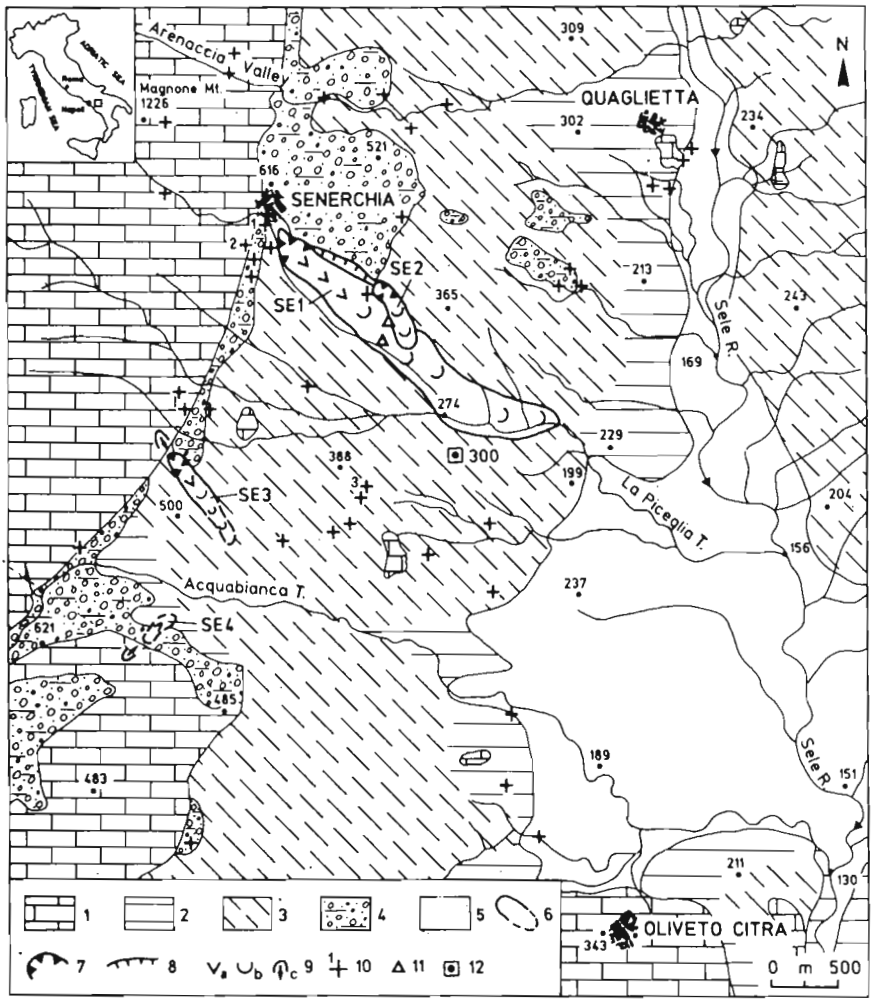

Figure 1 - Geological and hydrogeological schematic map and geomorphologic characteristics of studied landslides. 1) limestone and dolomitic limestone, middle to very high relative secondary permeability due to fracturing and karstification; 2) clayey-marly flysch with calcareous, arenaceous or calcareous-marly interbeds or blocks, very low to low relative primary permeability, middle secondary permeability of the higher part due to landslide remoulding in landlside areas; 3) like the previous one but affected by ancient or recent landsliding activity; 4) detrital and breccia deposits of rock fall or scree, carbonatic or piroclastic nature, middle to high relative secondary permeability also due to fracturing and remoulding; 5) alluvial deposits, middle relative primary permeability; 6) boundary of landslide body, broken line where uncertain; 7) crown with evident main scarp; 8) secondary landslide scarp; 9) rototraslational or traslational sliding (a), debris or earth flow (b), rockfall (c); 10) spring and its number if mentioned; 11) disappeared spring; 12) climatic gauge.

or piroclastic nature.

4) The alluvial deposits (Pleistocene-Holocene) are present along the course of the Sele River and its main tributaries.

As a result of the Apennine tectonics -begun in the Middle - Upper Miocene and still active throughout the Plio-Pleistocene-, the local rocks suffered large scale dislocations and associated intensive deformations (Cotecchia et al. 1992). The present morpho-structural setting of the upper Sele River valley has been mainly shaped during the last Lower Pliocene - Quaternary events (Parise et al. 1997).

The areas where carbonate rocks crop out are only marginally influenced by mass movements; they include mostly rockfalls and topples limited to the steep slopes (mean slope > 30°) bordering the carbonate massif. The flysch areas are characterised by low-medium acclivity slopes (10÷12°), and widespread creep and landslide phenomena (Agnesi et al. 1983, Budetta 1983, Cotecchia et al. 1996).

2.1 Hydrogeological features

The major hydrogeological features at the slope scale are briefly set forth.

In the area surrounding Senerchia, on the right side of the Sele River, the only detectable hydrogeologic unit is that of Mts. Polveracchio-Rainone (these mounts, which are not included in Figure 1, area found on the left of Magnone Mt.) (Celico & Civita 1976, Celico et al. 1987). It is formed by carbonate rock.

These rocks exhibit the highest relative permeability, owing to fracturing and karst phenomena. The carbonate rocks, some thousand meters thick, outcrop above the limit which establishes a contact with the remaining two significant hydrogeological lythofacies, the detrital and breccia deposits and the flysch. In the most depressed point of such a contact, the main springs of the hydrogeological unit are found (the Piceglia - Abbazzata springs, spring no. 1 and 2 on Figure 1, about 570 l/s).

Moving towards the valley, the carbonate mass, divided in scales by the tectonic activity, underlies for some hundred metres. Some of these scales are uplifted and almost surfaced. Thus, the Pozzo S. Nicola spring is formed (spring no. 3 on Figure 1, about 180 l/s).

The detrital and breccia deposits outcrop mostly in a limited quadrangular area, equal to 0.5 square Km, which is in contact, to the west, with the carbonate rocks, and is threatened by the adjoining SE1 and SE2 landslides in the south and an ancient landslide to the east. Its relative permeability is medium to high. The estimated thickness is of one hundred metres. The flysch lies at the bottom. On the upslope side, it is hydrogeologically in contact with the main aquifer. The deposits make up a secondary aquifer.

Wherever the flysch does not outcrop, it underlies the remaining lythofacies with which it is in contact. Its thickness reaches some hundred metres. With respect to the carbonate hydrogeological unit, this complex acts as an impervious bounding, with a continuous permeabilty limit, for the carbonate rocks and the detrital deposits. The soils making up this complex have been generally remoulded by a sequence of tectonic events and overlapping mass movements (Figure 1, Budetta 1983, Agnesi et al. 1983). These mechanical actions have disturbed the original structure of the soil and occasionally favoured some localized improvements of the hydrogeological features. Lastly, some surface-alteration phenomena have participated in setting up particular conditions favourable to groundwater flow.

The role of impervious limit played by this complex does not improve the stability of the slope Senerchia spreads upon. Some losses from the two hydrogeological water-bearing lithotypes towards the area under study have to be assumed, given:

- the occurrence of conspicuous springs of the main aquifer, located along the slope where the flysch outcrops (spring no. 3 on Figure 1, 360 m a.s.l.), far from the permeability limit which is found at 600 m a.s.l.;
- the precise match of the permeability limits around the secondary aquifer, near the scarps of landslides;
- the occurrence of some perennial old springs around the secondary aquifer, having an estimated discharge which exceeds ten litres per second;
- the after landsliding disappearance of some old springs.

3. THE HYDROLOGICAL-STATISTICAL METHOD TO STUDY THE RAINFALL INFLUENCE OVER LANDSLIDES

As to the role played by precipitation on slope instability, a lower limit can be easily

established. These phenomena are actually included among the "stresses" commonly undergone by a slope. Therefore, researchers must proceed with extreme caution while assuming slope instability to be triggered by precipitation, whenever these phenomena have been concomitant with heavy rainfalls (Polemio 1993).

Precipitation may prove the only cause when rainfalls are rather exceptionally heavy. As a rule, the slope stability happens to be already endangered by previous events (Polemio 1995 b). While investigating the relationships between precipitation and landslides, the behaviour of the territory should be taken into account. Each territory pursues a dynamic equilibrium under locally ordinary climatic stresses, provided they last long enough. As soon as extraordinary hydrologic events intervene, the equilibrium might be drastically changed (Govi et al. 1985).

Therefore, the analysis of any precipitation-induced impacts cannot disregard the vast array of instability-triggering phenomena in the case in point or within the investigated area. In particular, it must be generally agreed that a single precipitation-landslide event, though conspicuous, is but a time-limited event within a long-lasting active evolution (Polemio 1993).

Determining the influence of rainfall upon landslides requires a thorough approach that is possible only if an overall understanding of the soils forming the slope has been acquired.

Given the complexity of slope stability-related phenomena and the uneven variation speed of the stability conditions induced, simulations are required of both subsoil and surface phenomena.

Wherever groundwater flow is involved, attention should be focused on both the saturated and the unsaturated zones, and complete hydrological models of slopes must be constructed (Beven et al. 1987). Despite their complexity, however, such models do not cover some phenomena that cannot be overlooked, such as the air reverse flow in the unsaturated zone.

A full approach can only be derived from a deep knowledge of the slope soil behaviour. It is rather difficult to gather data enabling to reconstruct both underground and surface flow, focusing on percolation in the saturated and unsaturated areas.

The feasibility of physically-based models leading to run-off was first envisaged by Freeze and Herlam in 1969. These models had the merit of relying on processes and parameters directly observable on site.

Nowadays the unprecedented outburst of numerical calculation allows to build complex hydrologic models for vast basins. However, a problem remains to be overcome. Data are insufficient to indicate reliable results (Polemio 1995 a). Therefore, it is hardly surprising that these models have often been used in a inverse way with a view to deriving reliable value-lags of the hydrologic parameters of the investigated area, based on model calibrations.

Despite simplifying assumptions, it is self-evident that these models are rather complicated. They require many parameters which are practically unavailable. Gaining a preliminary and thorough knowledge of the slopes to be simulated proves extremely costly (Polemio 1995 b). Besides, difficulties arise in identifying these parameters within a complex hydrogeological context, as the Senerchia hillslope.

3.1 *The applied hydrologic-statistical method*

Should the numerous expensive data required to evaluate the above mentioned phenomena not be available, valuable indications can still be obtained by more streamlined hydrological/statistical models. Usually, these are empirical or semi-empirical models of the analysis of rainfall-landslide relation. Among them, the hydrological/statistical models were devised as a means of investigating, through the study of the selected hydrological variable, to what extent the rainfall event believed to be associated with a given landslide had been exceptional (Polemio 1993).

Experience has shown the way precipitation exerts an influence on the stability of some given slope types. Regardless of the soil nature, heavier and short-duration rainfall generally trigger limited surface-movements (Govi et al. 1985), often associated to new slipping surfaces. By contrast, long-duration rainy periods reactivate pre-existing slipping surfaces, mostly located some metres below the soil surface.

Consistently with the above scenario, Cascini and Versace (1986) indicate that for deep-seated landslides, the only significant variables are the ones which take into account rainfalls lasting more than one day.

Some new hydrologic variables need to be introduced afresh, such as the so-called cumulated or cumulative rainfall, that is the summation of precipitations occurred over a given number of consecutive days, prior to the considered day. The identification of the most suitable variable for the correlation between rainfalls and landslides results from essays run on more than one cumulative rainfall. The suggested method (Polemio 1993) leads to the identification of the critical duration. This is the number of consecutive days during which total rainfalls may prove significant for landslides, under given climatic and geomorphologic conditions.

The proposed hydrologic-statistical model investigates the exceptional character of the meteoric event which is likely to be associated to landsliding, by exploring the assumed maximum values of the selected hydrologic variable. As to surface-instability phenomena, the time-lag used to define the hydrologic variable, expressed in terms of precipitation intensity, is generally very short (a few days, at the most). Longer periods, ranging between 180 and 360 days are covered by means of cumulated rainfalls, in case of major landslide reactivations.

However, studies of statistical hydrology suggest the use of two parent functions or probability distribution functions (Polemio 1993 and references therein). The GEV (Generalized Extreme Value) function is univocally defined by the three parameters scale, position and shape, with the well-known Gumbel function being one particular case. In some particular hydrological situations (Cotecchia et al. 1995) it is necessary to utilize a parent function defined by means of a two-component model. These are four-parameter functions such as TCEV (Two Component Extreme Value), obtained by superposing two functions applied to the same set of data.

In theory, the larger the number of parameters in the parent distributions, the more closely will the investigated phenomenon be represented. On the other hand, due to the limited number of available data, the functions become more and more inaccurate and ineffective as the number of parameters is increased. The use of the three-parameter GEV function has by now become a very common practice, but efficacy in those cases where the separation condition (Matalas et al. 1975) occurs is rather poor. In such cases using more complex mixed functions, such as the TCEV, is justified.

The method described was applied to the variables, cumulative daily rains $Ch_{n,j}$:

$$CH_{n,j} = \sum_{i=j-n+1}^{j} H_i$$

where n stands for 1 to 180 consecutive days, j is the serial number of the day on which measurements were taken over the observation period and Hj is the daily rainfall of "j" day. The highest values $CHMAX_{n,y}$ were extracted, for each year y, from the generated series of data. The observation period is 65 years long.

By means of these models, the exceptional character of landslide-related rainfall events can be explained in terms of recurrence intervals or return period, T. As a result, one can determine the statistical cyclicity by which a slope has been subjected to hydrologic conditions similar to those related to a landslide.

It is interesting to consider that only this type of approach permits an evaluation of rainfall significance for historical landslide; the only condition is to know daily rainfall data. Available historical data about previous reactivations of the landslide body enable to better appreciate the cause-effect relationship (Polemio & Sdao 1996 a, b and d). However, once the influence of precipitation has been ascertained, the calculation of the return period may prove an useful prevention tool, all the more if it is associated to the detection of warning- "hydrologic thresholds". Moreover, whenever stabilization actions are foreseen, this method allows to assess the utility of works aimed at limiting the effects of precipitation on slope stability.

On the other hand, where a large area periodically investigated shows a severe susceptibility to landslides, often involving urban areas, a regionalized hydrological approach may be envisaged. This method could then prove a good choice (Parise et al. 1997, Polemio & Sdao 1996 b and e).

Within the framework of evolution processes, the assessment of the exceptional character of rainfalls resulting in landslides may support the geomorphological and evolutionary study (D'Ecclesiis et al. 1991, Cotecchia et al. 1995), as in this research.

The hydrologic and statistical results inferred, irrespective of the soil nature and the

probability grade	1	2	3	4	5	6
return period (y)	<2	2÷5	5÷10	10÷20	20÷50	>50
rain influence	negligible	secondary	modest	significative	considerable	exceptional
landslide hazard	very low	low	modest	middle	high	very high
history case	SE1, SE2	SE3 (5÷20)	SE4 (30)			

Table 1 - Probability grades of cumulative rainfall related to landslide. History case: landslide name and the critical duration in brackets.

problem geometry, have always proven consistent with the slope hydrogeological conditions and the characteristics of the soils involved. In every investigated case, given the grain-size fractions, the corresponding hydraulic conductivity and the thickness of the landslide body, the duration of a critical infiltration episode has been estimated - as is the case in the Agrigento landslide (Cotecchia et al. 1995). The duration was always found to be almost equal to the critical duration or the duration of the most hydrologically and statistically significant cumulative rainfall.

The aforementioned positive sides of this method are discussed in detail in the bibliography (Polemio 1993, Cotecchia et al. 1995, Polemio & Sdao 1996 a-e).

Unlike the work done on the rainfall/flood correlations, the rainfall/landslide research deals with a subject -the slope- which, contrary to catchment areas, changes its own characteristic morphological, and often geotechnical, features with succeeding landslide events. This implies theoretically that, when constructing a trigger model, one should consider from a statistical viewpoint the time lapsed since the last movement or morphological change and the scale thereof. Integrated studies should be undertaken on statistical hydrology and evolving morphology (D'Ecclesiis et al. 1991, Cotecchia et al. 1995).

Attention should be focused on the influence exerted by some hydrological events on slope stability rather than on trigger thresholds. To this particular purpose a classification of the influence of rains on slope stability and of rain-induced landslide hazard is proposed here (Table 1).

case	date	type	depth	width	length
SE1	11/1980	mudslid e	30	350	2500
SE2	12/1993	mudslid e	10	100	570
SE3	11/1996	mudslid e	<7 ?	70 ?	800 ?
SE4	12/1996	debris flow	<6 ?	50 ?	250

Table 2 - Investigated landslides and average features (m).

4. INVESTIGATED LANDSLIDES

The SE1 landslide was mobilized following the 1980 earthquake (M = 6.8): the mudslide measures about 2500 m in length (Table 2); the landslide is likely to be a reactivation though no historical data are available (Cotecchia 1981 and 1984, Cotecchia et al. 1986, Maugeri et al. 1982). Despite the 1930 and 1962 earthquakes (9÷10 MSK degree), the 1955 aerial photos do not show any well-defined landslide body; only in the area between 274 and 199 m a.s.l. landslide activity is recognizable (Maugeri et al. 1982, Budetta 1983). It is a complex landslide, started as a translational earth slide in the upper portion and evolved to flow in the medium-lower one. The main scarp is located in the proximity of the contact between the flysch and carbonate or detrital deposits.

The initial landsliding coincided with the collapse of the aqueduct which crossed the landslide body.

The SE2 landslide represents the enlargement of a subsidiary slide situated in the middle-upper portion of the left flank of the SE1 landslide (Table 2, Photo 1). The reactivation of a lateral portion of the SE1 mudslide was observed on December 29, 1993, with a strong retrogressive evolution. The SE2 accumulation zone is superimposed on or joined to the SE1 landslide body. This landslide is continously surveyed from 1995 and it is still active today (Polemio 1996). The SE2 landslide ground surface inclination ranges from 10 to 15°, without significant changes due to landsliding (Wasowski 1994); the main scarp is very

Photo 1 - Panoramic view of the SE1 and SE2 landslides.

steep, its slope continuously changes up to 50°.

The landslide body shows partial excursive accelerations mainly due to upslope feeding. In fact some secondary rotational slides, falls and earthflows, located along and near the crown, periodically load the body upslope, thus feeding the flow; the landslide is composite (Cruden & Varnes 1994). The maximum displacement rate was 1.33 m/day (72 m after 54 days) and was observed at the main scarp bottom.

The SE2 landslide represents a geological hazard for some houses and infrastructures located upslope in the surrounding area.

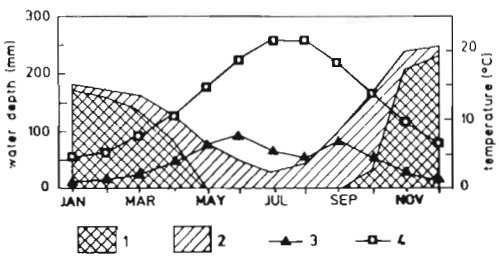

Figure 2 - Hydrological regimen. 1) surplus water, 2) rainfall, 3) real evapotranspiration, 4) temperature.

Photo 2 - The SE4 landslide foot.

Here again, the initial landsliding coincided with the collapse of the aqueduct which ran longitudinally through the landslide.

The SE3 and SE4 landslides occurred in Sierra Piano and Bosco, respectively, are very recent. The Author was thus able to carry out surface surveys without resorting to topographic surveys and aerial views. Needless to say, the detected geometrical and geomorphological features are but preliminary ones.

Some points of similarity do exist between the SE3 and SE2 landslides as to the particle size of the soils involved and the motion thereof. However, there is an essential difference. The evolution of the landslide is not retrogressive. It was favoured by the failure of the rock overlying the landslide crown. Therefore, the SE3 landslide would appear more similar to the SE1 landslide, though the latter is by far smaller. It might result from the reactivation of a slightly bigger landslide interested by not-structural stabilization works. The failure of the overlying rocks threaten both the road and the aqueduct connected to some large tapped springs. Moving downward, the mudslide flowed past a gravity wall of massive stones destroying the underlying local road and the telephone lines. In the vicinity of another severely damaged road, not far from the foot of the landslide, the motion was all the more complex.

The SE4 landslide differs from the remaining ones, as it affected a detrital calcareous body. The motion, enhanced by

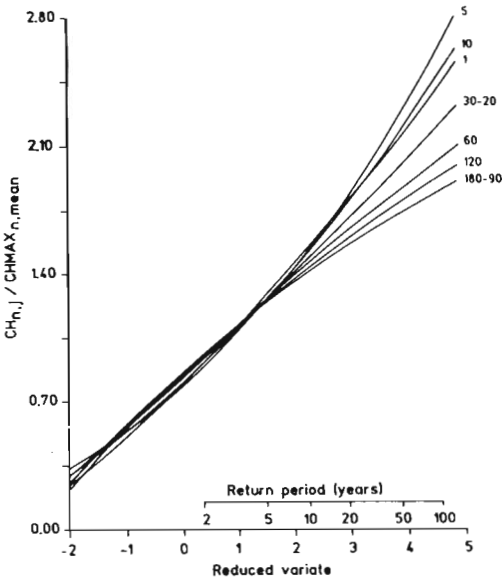

Figure 3 - Probability distribution functions of Senerchia cumulative rainfall. $CH_{n,j}$ = cumulative rainfall value, $CHMAX_{n,mean}$ = mean yearly maximum of cumulative rainfall.

failures occurred above the crown lacking the main scarp, was mostly translational uphill and debris-flow-like downhill. The landslide destroyed an important aqueduct and a local road which ran transversally through it and it almost wiped out a house built next to the foot. The motion lasted less than 24 hours (Photo 2).

Except for the SE1 landslide, Senerchia landslides are known to have been triggered by concomitant heavy rains. This thesis expressed by the local population and some scientists is based on the notion that landslides occurred during rainy periods. We will show how inaccurate this view is.

4.1 *Rainfall associated with landslides*

There is only one monthly temperature and rainfall minimum and maximum during the mean year of Senerchia (600 m a.s.l.) (Figure 2). Precipitation is influenced by the vicinity of the Tyrrhenian Sea and the mountain. The mean annual rainfall is 1600 mm, the mean annual temperature is 12.8 °C. According to the Thornthwaite-Mather method (1957), evapotranspiration is 570 mm, so 1030 mm are available for infiltration and runoff. Hence, hydrogeological conditions are mostly prone to landsliding between November and May. The four mentioned landslides occurred in November and December.

While studying the nine series of $CHMAX_{n,y}$ of Senerchia, the separation condition was not found. It follows that the probability distribution functions of cumulated rainfalls were calculated using the GEV function (Figure 3). Note that the curves resulting from the standardisation by means of $CHMAX_{n,\ mean}$ - the mean of annual maximum values - are similar. If a single mean curve was assumed for T<20, the maximum deviation would equal 12% of the mean, at the most. This circumstance, common to all the sites investigated so far enables to set up simple warning tools.

Once the probability distribution functions were known, the return period of all cumulated rainfalls 60 days before and 30 days after the landslide occurrence was calculated. Each rainfall-landslide event was then assigned the corresponding probability grade (Table 1). The critical duration of the SE1 and SE2 landslides was not determined, given the negligible role played by rainfalls.

The analysis confirms that the SE1 landslide was activated during ordinary rainfalls (Cotecchia & Nuzzo 1986).

Furthermore, in contrast to the hypothesis put forward by other Authors (Wasoski 1994), the reactivation of the SE2 landslide cannot be associated with rainfalls. The concomitant rain was a contributing factor rather than a determining factor, acting on a pre-existing precarious stability. Lacking the seismic action involved in the SE1 case, the landslide is accounted for the evolution of the Sele Valley sides - briefly discussed in the conclusions - still undergoing a complex dynamic process.

The SE3 and SE4 landslides occurred during a relevant rainy period - in late 1996 - when the yearly rainfall rate was 25% higher than the mean values.

The SE3 landslide was affected by rainfalls, the role of which is secondary though not negligible. The scheduled studies, including on-site surveys and hydrogeological determinations, will enable to check the physical reliability of the estimated critical duration (Table 1). The low value of the critical duration, given the particle size and the depth of the landslide body, is justified by the pre-existing strong remoulding of the landslide.

The SE4 activation is partially ascribable to the action of rainfalls 30 days before the event.

As to the recent landslides, the collapse of rocks above the crown, which can be hardly dated, contributed to the instability of the site.

5 CONCLUSIONS

This study highlighted the extreme complexity and diversity of the phenomena that govern the effects of rainfall upon slope stability. The study showed that conventional statistical hydrology methods, based on flood investigations and then applied to landslides, are misleading. Whatever trigger model is applied to the rainfall/landslide study, one cannot ignore recent slope changes. In the case in point, the progressive evolution of the Sele valley sides proved crucial. It followed recent tectonic events and resulted in a sequence of gravity phenomena. These instability phenomena pursue new conditions established by the geomorphological, seismic and climatic status which are still far from equilibrium. The single instability episodes have to be regarded as macroscopic and sudden signs of a slow, relentless evolution slightly affected by rainfalls.

The continuous hydrogeological monitoring started in 1995 on the SE3 landslide is likely to clarify the role played by groundwater flow within the carbonate aquifers that make up the uphill portion of the investigated slope.

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