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# Landslide hazard and critical rainfall in Southern Italy

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ABSTRACT: Heavy rains are very often responsible for extensive mass movements. It has been the aim of this work to highlight the existence and intensity of the influence exerted by such rains in triggering selected landslides in Southern Italy, with reference to their main geomorphological features. Simple hydrological/statistical methods are suggested to predict landslide hazard caused by heavy rains.

## 1 INTRODUCTION

Heavy rains are one of the main natural factors producing landslides as they may cause pore pressure to increase on slopes, modify the slope's geometry as a result of erosion and originate swelling and softening processes in clay soils. Some experiences show that very seldom will rains alone trigger landslides; rather they impair borderline conditions of stability due to the overall effect of different phenomena that determine the slope's morpho-dynamic evolution. It follows that one cannot define right away how landslides and rainfalls are inter-related unless one has a thorough knowledge of how the sliding slope's morphology has been evolving. The purpose of study was then to define the role of rainfall events on selected landslides occurring in Southern Italy. Landslides of interest for investigations on rainfall/landslide cor-relations were identified at the urban areas of Senise, Castronuovo S. A., Calciano and Agrigento (Fig. 1).

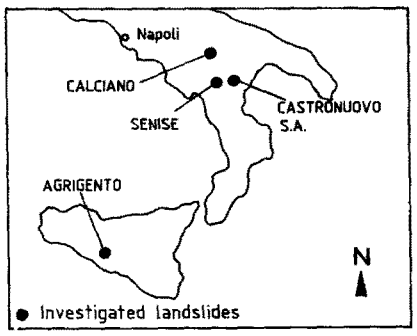



Fig. 1 - Location of examined landslides.

## 2 INVESTIGATED LANDSLIDES

The valley of Temples at Agrigento is characterized by the outcropping Pleistocene Agrigento Formation consisting, from below upwards, of marly or grey-blue sandy clays, medium to fine yellowish sand and calcarenites. Beneath that, as the grain size gradually decreases, the Monte Narbone formation (Pleistocene) is encountered which dates back to the Mid-Upper Pliocene and consists of marly and silty clays. The area is subject to severe geomorphological evolution as shown by the mobilization of large landslide bodies, many of which have been produced during this century. Among them, one can recognize the landslides of 1944, 1966 and 1976, designated as AG1, AG2 and AG3, respectively (Fig. 2): AG3 is the only landslide that was found to have been conditioned by previous precipitations (Cotecchia et. Al. 1995).

AG3 is a large rotational slide, followed by the frontal toppling of disjointed calcarenite blocks (Table 1). This landslide has occupied an area of approx 0,43 $Km^2$, of which as much as 0,28 $Km^2$ was already occupied by a previous slide body. The main

Table 1. Geometrical features of investigated landslides

| *Landslide* | *AG3* | *CSA2* | *CA1* | *S1* |
|---|---|---|---|---|
| data | 12/1976 | 4/1973 | 5/1985 | 3/1985 |
| slide type | rotational | rototranslat | rototranslat | translational |
| area ($Km^2$) | 0.43 | 0.20 | 0.05 | 0.003 |
| thickness | 18 - 22 m | 60 m | 20 m | 10 m |
| max lenght | 180 m | 500 m | 250 m | 55 m |
| max width | 325 m | 500 m | 200 m | 55 m |
| crown elev. | 100 m asl | 750 m asl | 325 m. asl | 370 m. asl |
| toe elev. | 60 m. asl | 650 m asl | 240 m. asl | 350 m. asl |
| gradient | 17° | 12 ° - 15 ° | 18 ° | 19 ° |
| involved geology | Calcareni-te-sand-clay | Conglomer ates-sands | Marly clayey flysch | Sands |

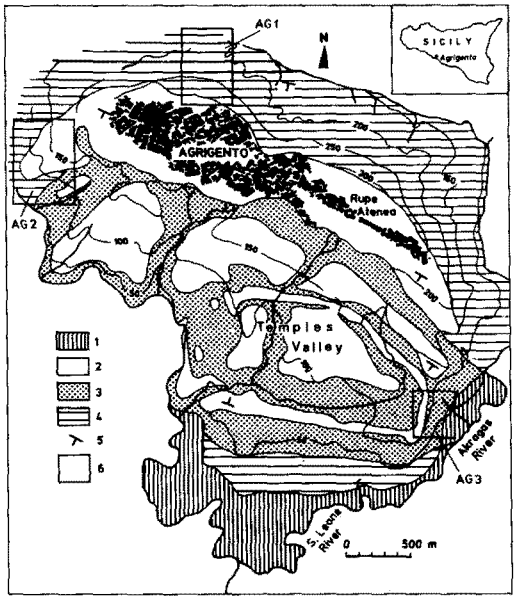



Fig. 2. Agrigento schematic geological map and landslides: 1) Alluvia; 2) Calcarenite; 3) Clay and sandy clay; 4) Clay and marls; 5) strike and dip direction of strata; 6) investigated landslides (after Cotecchia, D'Ecclesiis & Polemio, 1995).

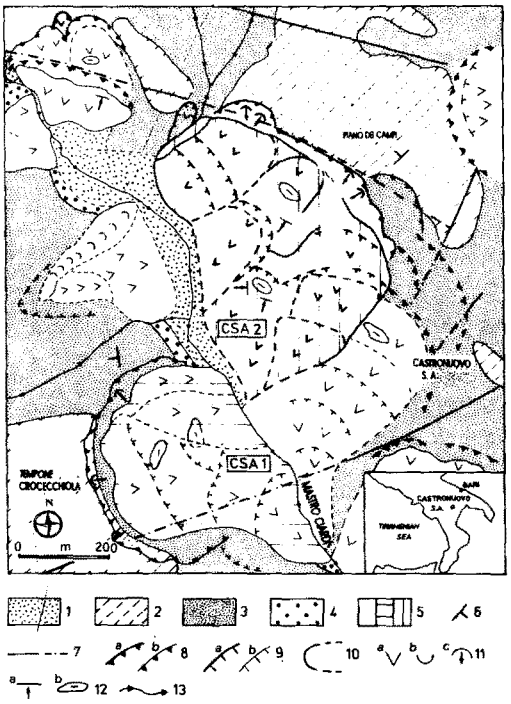
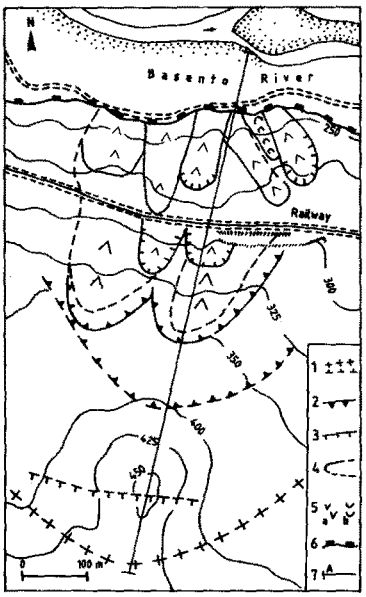



Fig. 3. Geomorphological map of Castronuovo S. A. landslides: 1) Backfill; 2) Sands and conglomerates of Serra Corneta (Lower-Middle Pleistocene); 3) Castronuovo Conglomerates (Lower-Pleistocene); 4) Aliano sands (Lower Pleistocene); 5) Landslide debris (a), CSA1 (b) and CSA2 (c) landslide body; 6) Attitude of beds; 7) Tectonic joint, broken line where it is assumed; 8) Main scarp of landslide, broken line where it is assumed, present (a) and recent or old (b); 9) Secondary scarp of landslide, broken line where it is assumed, present (a) and recent or old (b); 10) Boundary of the sliding body: broken line where it is assumed, boldface where it is acitve, thin line where it is quiescent or stabilized; 11) Sliding (a), flow (b), rockfall (c); 12) Countersloping surface (a) and morphlogical depression (b); 13) surface drainage line.

scarp, mostly running along a pre-existing fracture, extends at an elevation at 100 m asl and borders a landslide body, at least 22 m deep.

In April 1973 a huge rototranslational slide, called CSA2, disrupted an extensive portion of the suburban area at Castronuovo S. A. and severely injured some of the urban infrastructures (D'Ecclesiis et Al. 1991) (Fig. 3). In this portion of territory a pleistocenic sequence crops out consisting, from below upwards, of fine-grained, loose or more compact, quartzy- carbonate sands, hosting silt or clay levels; poligenic conglomerates with a sandy, or silty-sand matrix, either loose or closely cemented; sands, silty sands and scarcely cemented, or uncemented, reddish conglomerates. This sequence, which is conditioned by a monoclinal setup, appears to be heavily affected by fractures and faults oriented along two main tectonic directrices (WNW - ESE and NE - SW). The CSA2 landslide, covering an area of which at least 70 % had been previously affected by other mass movements, can be ascribed to a roto-translational slides (Fig. 3 and Table 1). This landslide is bordered along its upstream side by a clearcut tectonic fracture, mostly running along the main scarp: it extends over an area of about 0,3 Km2 and its maximum thickness is in the order of 50-60 m. The CSA1 is a large rotational slide occurred on 1953 in similar geomorphological conditions of CSA2 landslide.

The CA1 landslide is located quite close to the built-up area of Calciano (Fig. 1); it is developed in the structurally complex formation ( Serra Palazzo Flysch) consisting of a strongly fractured and deformed succession of marly limestones, clay marls and marly clays containing sandstone layers and masses. The CA1 landslide is a partial remobilization of an ancient multiple rototranslational slides which originated at the margins of a vast area affected by deep gravitational slope deformations (Grassi et al. 1993). The main scarp of ancient landslide extends at elevation between 325-400 m asl while its foot portion is very likely buried below recent and present deposits of the Basento river (Fig. 4). The main slip



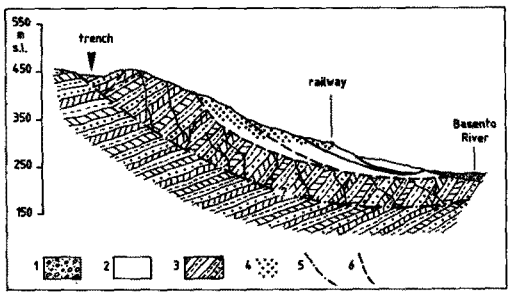




Fig. 4. Calciano landslide. A) Geomorphological map: 1) Possible rupture surface and edge of the trench due to deep-seated gravitational slope deformations (D.S.G.S.D.); 2) main scarp of ancient and recent landslide, when degraded are marked by a dashed line; 3) scarp of present landslide; 4) limit of landslide body; uncertain limit are marked by a dashed line; 5) compound slide (a) and earthflow (b); 6) edge of river bed; 7) section line. B) Geomorphological section: 1) alluvial deposits; 2) landslide debris; 3) Serra palazzo Flysch likely to be affected by D.S.G.S.D. 4) swelling deformation phenomena caused by D.S.G.S.D.; 5) likely deep - seated failure surface trend; 6) sliding surface; continuos line represents CA1 failure surface (after Grassi et al., 1993.)

surface cuts into marly clays soils, and is located at depths of up to 30-40 m. In 1985, the mid-lower portion of an ancient landslide body underwent a significant remobilization (CA1) revealed by surficial displacements of a few meters and was a few centimeters deep. In depth, the movement occurred inside the old landslide body with two different slip surfaces: the deeper one is located at about 20 m below field level.

In the of winter 1984-85, the eastern urban area at Senise underwent some mass movements which caused remarkable damage (Catenacci 1993, Lazzari et al. 1991). The area shows outcrops of the Aliano Sands formation (Pleistocene), consisting of fine to medium-grained silty or clays sands, which may be either perfectly dissolved, though always firmly thickened, or may be loosely cemented. The formation is characterized by a monoclinal structure with down-slope dipping strata. The landslides that developed in March 1985 are located in the eastern urban portion: one is rather close to the Timpone Hill, in the Santa Maria delle Grazie neighbourhood, the other one, termed S 1, in the Aria Marina locality (Table 1) (Del Prete et al. 1991, Catenacci 1993). Both these landslides are partial remobilizations of a preexisting landslide body. S1 started inside an old landslide body underlying most of the eastern slope of the relief where Senise is located: it originates from a translational slide which occurred on a slip surface at a depth of about 10 m.

## 3. HYDROLOGIC STATISTICS OF CUMULATIVE RAINFALL

Determining the influence of rainfall upon landslides requires a thorough approach that is only possible if an overall understanding of the soils forming the slope has been acquired. To do so, one must develop a clear picture of the modes of surface and groundwater flow: where groundwater flow is concerned, 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, Cascini & Versace 1986). 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.

Should the numerous expensive data required to this effect not be available, precious indications can still be obtained by more streamlined hydrological models. Usually, these are empirical or semi-empirical models of the analysis of precipitation-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 has been exceptional (Polemio, 1993). Thanks to 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 considered in this study.

For sake of brevity, reference is here made to the attached bibliography. However, studies on statistical hydrology suggest using two parent functions or probability distribution functions, as in the examples described below (Polemio 1993). The GEV (Generalized Extreme Value) function is univocally defined by just three parameters, the scale, position and shape parameters (Jenkinson 1955), with the well-known Gumbel function being one particular case.

Matalas et al. (1975) showed that traditional parent functions, such as Gumbel's or GEV, are unable to satisfy the condition of separation. The condition manifests itself through the survey of a few values, known as outliers, so exceptional and significantly larger than the others that they seem to be statistically separate from the rest. In order to perceive this effect, probability distributions defined by the superposition of two or more distibution are applied, each relative to a single recognizable population. An example is represented by the parent function as defined by means of a two-component model (Rossi et al. 1984). These are four-parameter functions such as TCEV (the Two Component Extreme Value) obtained by superposing two functions applied to the same set of data.

The fact of using mixed functions not only has a statistical value, but it may also prove physically significant. Pegram & Adamson (1988) applied the TCEV functions to rains recorded in certain districts of South Africa. TCEV offers a perfect interpretation of the nature of two populations of data, one relative to local weather events and associated to the primary function, the other one due to local climate's synoptic traits described by the secondary function. The percentage of outliers occurring in the data was determined: it was observed that such percentage drops from 58% to 0% as one moves away inland from the coast where the effect of the impacting air masses of cyclonic origin is strongest.

In theory, the larger the number of parameters in the parent distributions, the more closely will the investigated phenomenon be represented. On 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; moreover, it becomes more difficult to determine the value of the parameters (Rossi et al. 1984). One will then have to proceed gradually and check at each step whether the results is reliable (Polemio 1993). Using the three-parameter GEV function has by now become a very common practice, but efficacy in those cases where the separation condition occurs is rather poor. In such cases using the more complex mixed functions, like TCEV, is justified.

## 4 INVESTIGATED RAINFALL-LANDSLIDE

The climate in the four investigated areas (Fig. 1) is determined by the maritime, or Mediterranean, type of rainfall and by moderate temperetures; average low annual rainfall and high temperatures originate a sub-humid to semi-arid climate (Polemio 1993).

The method described earlier in this work was applied to the variables, cumulative daily rains $PC_{n,j}$, where n stands for 1 to 180 consecutive days and j is the serial number of the day on which measurements were taken over the observation period of about 60 years. The highest values $PCMAX_{n,y}$ were extracted, for each year y, from the generated series of data.

The results of studies on hydrological statistics and evolving morphology are summed up, for sake of brevity, in Fig. 5 (Polemio 1993, Polemio & Dragone 1993, D'Ecclesiis et al. 1991, Lazzari et al. 1990). It was thus realized that, particularly in those case where the reccurrence interval T is less than 10 years, the investigated slopes were found to be stable during the rains whose cumulative variables, whichever n is, had longer reccurence intervals than those that can be associated with the landslide: this is the most difficult problem encountered when working on the rainfall/landslide correlation.

Over the years, many models describing landlside-triggering rains were analysed, generally found to be of no practical use for the purpose of preventing calamities or of allowing various sites to be compared in connection with hazard conditions.

The empirical expressions relating intensity/duration of preceding rain allow simple and convenient critical straight curves to be defined in a log-log plane (Caine 1980, Gostelow 1991). Such critical curves change in agreement with local climate and geomorfology, often giving uncertain indications on possible links between preceding rains and landslides produced (Jibson 1989, Polemio 1993, Cotecchia et al. 1995).

For a rapid estimation of the hazard of rains, as they occur, or of their influence on fallen slides, it is proposed to define the generalized or normalized cumulative variables H by means of simple statistical variables. For each of the seven slides considered in this work, the following expression was calculated for the 60 days preceding each event:

$$H_{n,j}=(PC_{n,j}-PCMAX_{n,MED})/(PCMAX_{n,MAX}-PCMAX_{n,MIN})\%$$

where MIN, MED, MAX represent the lowest, mean and highest values, respectively, for each series of data $PCMAX_{n,y}$ (Fig. 6). For landslide AG1, the only

H variables appearing inside the significant interval are those corresponding to n=120 to 180; only for n=180, H takes positive and growing values as the landslide approches. For slide AG2, H is always less than 1. For AG3, the H variables were found to be representable in the selected interval with any one n. Note that for n>60, the H variables rise steeply before the slides: the highest H value (55) is reached by $H_{120}$. Consider that the H variables were negative for CSA1, while for CSA2 the generalized cumulative rainfall H, not represented here for brevity, were hardly above 1 only five days before the slide; the highest H value (14) was taken by the variable on the landslide day for n=60 and n=120. For CA1, our findings were similar to those described for AG3: for n=120 and n=150, H rises prior to the slide and takes peak values of about 70. For S1, the only H variables appearing inside the significant interval are for n>30; immediately before the slide, H is higher than 1 only for n>90. The highest H value was reached for n=120 and was equal to 20. It should be noted that at the n value at which $H_{n,j}$ was found to attain its highest value, there corrisponded the largest $Pc_{n,j}$ recurrence interval for for all the investigated slides. Thus the representation proposed by Polemio (1993) produces expedient results that are in line with the hydrological and geomorphological studies carried out by several investigators (Polemio 1993, D'Ecclesiis et al. 1991, Lazzari et al. 1990); it also provides a tool by which one can compare the cumulative variables graphically - with whatever value of n - in relation to rainfall/landslide events at one or more sites. A graphic representation of the type proposed here offers the advantage that one can display the precipitation gradient over time: a persistent negative gradient prior to the landslide event seems to rule out the existence of a cause-to-effect relation. A value of H approximately equal to, or higher than, 25 could be associated with a low-middle landslide hazard.

The latest studies indicate that useful trigger models are those based on the Antecedent Precipitation Index (API), often a geometrically weighted API. A recent research work, based on API application to 18 rain/landslide events occurring in Southern Italy, shows what are the limits to this approach (Naden et al. 1993).

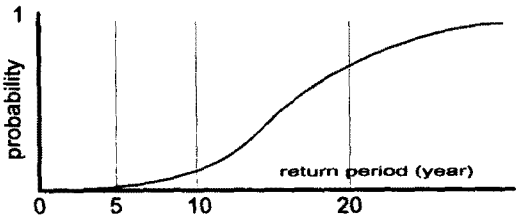
Unlike the work done on the rainfall/flood correlations, the rainfall/landslide research deals with a subject -the slope- which, contrary to catchment areas, changes its own characteristic morphological, and often geotechnical, features with succeeding landslide events. This implies that, when constructing a trigger model, one should consider from a statistical viewpoint the time lapsed since the last movement or morphological change and the scale of these.

By a correct approach, one should undertake integrated stuides on statistical hydrology and evolving morphology, especially targeted to the definition of trigger models (D'Ecclesiis et al. 1991, Cotecchia et al. 1995). In this respect, continuous and seasonal kinematically slow slides that are mobilized every 2 to 5 years in the average, are scarcely significant.

Rather than talking about trigger thresholds, one should talk of the hazard that certain hydrological events will influence slope stability. A classification of the influence of rains upon slope stability and of rain-induced landslide hazard has been worked out and is proposed here for this particular purpose (Fig. 5). As T increases, so do rain influence and landslide hazard; for the proposed landlside probability curve is a conceptual value: it will have a zero tangent for T=0 and will reach the limit value 1 as T approaches to infinity. Once we can use a larger number of case-studies and when the conclusions described in the two preceding paragraphs have been interpeted, we will be in a position to define better the landslide parent function.

## 5 CONCLUSIONS

This study highlighted how complex and how very diverse are the phenomena that govern the effects of rainfall upon slope stability. By having recourse to normalized cumulative variables, we obtained a fast graphical tool indicating the quality of the results that eventually emerged, and one that is of considerable use when rainfall/landslide events occurring at different sites are compared. The study showed that




| | | | | |
|---|---|---|---|---|
| rain influence | negligeble | secondary | significative | considerable |
| landslide hazard | very low | low | middle | high |
| history case | AG1(3),AG2(1) ,CSA1(1),S1 | CSA2(5) | | AG3(24), CA1 |

Fig. 5. Rainfall return period and landlside probability. History case: in parenthesis return period (year) if it is known.

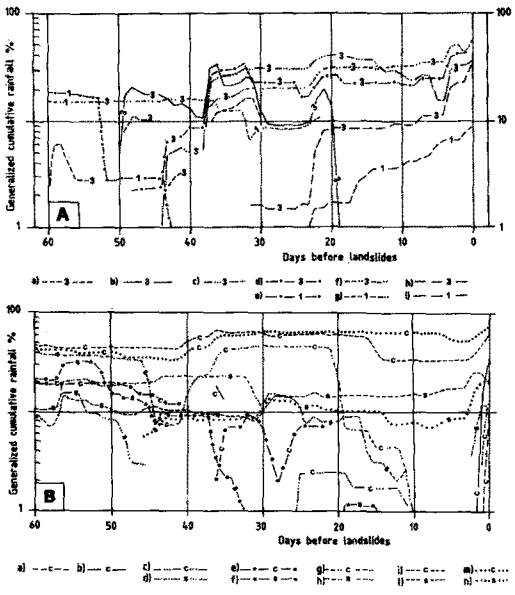



Fig. 6 - Hydrograms of generalized cumulative rainfall. A: a), b), c), d), f), and h) n=20, 30, 60, 90, 120, 180 d, AG3 landlside; e), f) and i) n=90, 120, 180 d, AG1 landslide. B): a), b), c), e), g), i) and m) n=1, 5, 30, 70, 90, 120, 150 d, CA1 landlside; d), f) h), l) and n) n=30, 70, 90, 120, 150 d, S1 landslide.

statistical hydrology conventional methods, borrowed from investigatons on floods for applicaton to those on landslides, are misleading. Whatever trigger model is applied to the rainfall/landlside study, one cannot ignore recent slope changes.

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