Geogr. Fis. Dinam. Quat.
22 (1999), 115-128, 7 figg.

ILEANA CORBI (*), PANTALEONE DE VITA (*), DOMENICO GUIDA (*),
MATTIA GUIDA (**), ROBERTO LANZARA (*) & ANTONIO VALLARIO (**)

MID-TERM GEOMORPHOLOGICAL EVOLUTION OF THE COVATTA VALLEY, BIFERNO RIVER BASIN, MOLISE, ITALY

ABSTRACT: CORBI I., DE VITA P., GUIDA D., GUIDA M., LANZARA R. & VALLARIO A., *Mid-term geomorphological evolution of the Covatta valley, Biferno river basin, Molise, Italy.* (IT ISSN 0391-9838, 1999).

On April 12, 1996, a complex system of landslides involved the left side of the Biferno River (Campobasso, Molise), in the Covatta area, interrupting the State Highway 647 and damming the Biferno River, forming a lake.

Previous studies consisted of a geological survey and production of a geological map, as well as geomorphological analysis of the landslide of April 12, 1996,. In the Covatta area, several mass movements (translational-rotational slides and lateral spreading), which become rapid earth-debris flows in their terminal regions, have been generated. Progressive sliding of secondary earthflows has divided the landslide of April 12, 1996, into many different subsystems, each of which is characterized by various lithological associations and different morphologies. Fig. 1 is a synthesis of this and shows both the geological situation and the typology of the landslide subsystems. A new substantial movement of the landslide occurred in the Spring of 1997, making the slopes smoother in the upper part and the soils more fluid in the central and lower parts.

This work is a report on the study that has been developed on the morphoevolutive phases of the slope analyzed during the years before its final collapse and their relationship with the rainfall patterns. Examination of the slope's morphological stages in the period 1954-1997 and the analysis of the hydrological parameters has shown that the morphological features were mainly governed by a sequence of extraordinary climatic conditions.

The heavy rainfalls and snowfalls in the Winter of 1986, for example, produced an acceleration of the slope's evolutive phenomena, whereas their deceleration in 1992 should be considered a consequence of the very low rainfalls of the previous three years.

Actually, in the case of deep phenomena like that of April 12, 1996, it is very difficult to predict the time necessary to prepare the slope collapse; it is in any case considerable (at least several decades). On the other hand, most of the single, small phenomena are assumed to occur in a period of a few years, because of slight increases in the water surplus.

KEY WORDS: Landslide system, Mid-term evolution analysis, Covatta valley, Molise, Italy.

RIASSUNTO: CORBI I., DE VITA P., GUIDA D., GUIDA M., LANZARA R. & VALLARIO A., *Evoluzione geomorfologica a medio termine del Vallone in località Covatta (Bacino del Fiume Biferno, Molise).* (IT ISSN 0391-9838, 1999).

La presente nota fornisce un'analisi morfoevolutiva a medio termine del vallone nel quale, il 12 Aprile 1996, in prossimità dell'abitato di Ripalimosani, si è sviluppato un vasto fenomeno franoso che ha determinato l'ostruzione della valle del Biferno. L'analisi, effettuata su aereofoto e su cartografia a varia scala, ha avuto lo scopo di ricostruire le tappe della evoluzione recente del piccolo bacino idrografico, relativamente al periodo 1954-1997. Le sequenze geomorfologiche ricostruite sono state comparate con i dati dell'analisi delle condizioni meteoclimatiche che si sono instaurate nell'area nello stesso arco di tempo. Da questo confronto è emerso che le reazioni morfodinamiche sono state, in genere, ritardate rispetto agli eventi climatici, con una «inerzia» che trova ragione nella scarsa permeabilità dei terreni affioranti; in ogni caso, le risposte morfoevolutive appaiono tanto più significative quanto più le sequenze pluviometriche hanno caratteristiche tali da favorire i fenomeni di infiltrazione efficace.

A medio termine la storia evolutiva di questo vallone ha attraversato periodi di relativa tranquillità morfogenetica durante i quali si è realizzata una ricarica funzionale del sistema e periodi caratterizzati, invece, da vivaci processi erosionali e denudazionali, ovviamente in relazione a una maggiore disponibilità idrica. Lo studio pone in evidenza che queste condizioni possono permanere per tempi abbastanza lunghi (dell'ordine delle decine di anni), durante i quali il sistema geomorfologico viene lavorato ai fianchi, con un progressivo abbassamento della soglia di resistenza, prima del collasso generalizzato; questo periodo si configura, quindi, come una fase di preparazione pre-parossistica. È stato infine rilevato che nella storia evolutiva del sistema franoso del 12 Aprile 1996, i fenomeni di colata hanno avuto un ruolo importante, sia prima che dopo la fase parossistica. I dati raccolti fanno ritenere che la presenza di diffusi fenomeni di colata su un versante instabile in terreni strutturalmente complessi possa rappre-

(*) *Geologist, external member of the research team.*
(**) *Dipartimento di Scienze della Terra dell'Università di Napoli «Federico II», Largo S. Marcellino 10, 80138 Napoli.*

M. Guida and I. Corbi performed the 1954-1997 geomorphological and morphoevolutional analyses; P. De Vita performed the hydrogeological analyses and the study of the meteorological conditions; D. Guida and R Lanzara. performed the analysis and the graphical elaboration of the landslide's May 1997 reactivation phase; A Vallario. organized the research outline and coordinated togbether M. Guida the phases of the study and refinements of the interpretations.

Financial support was provided by CNR 96.0025 e 97.00228.CT05 (M. Guida); 98.00636.PF42 (A. Vallario). Paper n° 2060 del G.N.D.C.I.

The authors would like to thank S. Perriello Zampelli for their helpful comments and critical revision of the English manuscript. Thanks are also due to G. D'Agostino, M. Franco, F. Mastellone and R. Spinelli for their assistance.

sentare un evento precursore delle mobilizzazioni generalizzate, proprie delle crisi parossistiche. Nelle fasi di modellamento post-collasso, invece, le colate completano lo svuotamento dei bacini di frana, caratterizzando così le sequenze evolutive terminali dei sistemi franosi complessi.

TERMINI CHIAVE: Sistema franoso, Evoluzione geomorfologica a medio termine, Vallone Covatta, Molise.

INTRODUCTION

In April 1996 a large lanslide phenomenon occurred in the Covatta valley of Ripalimosani, province of Campobasso, Molise, Italy), on an articulated slope whose morphology displays a marked control by the litho-structural arrangement. The collapse mobilized about 1 million cubic metres of material (Lanzara & *alii,* 1996; Guida D. & *alii*, 1996).

The landslide system (*sensu* Guida D. & *alii*, 1988) included a series of rotational and roto-translational slides and, subordinately, lateral spreads in the slope's upper and mid-upper area, while in its lower area the phenomenon can be classified as an earth-debris flow. The foot of the slide completely obstructed the Biferno river valley. As the heavy rains that occurred before and after the event had increased the river's flow by about 60-70%, in the valley upstream of the foot of the slide an artificial lake was created. It measures around 1,2-1,3 millions mc. To a large extent, the lake still exists today.

In Corbi & *alii*, 1996, the successions cropping out in the area of the slide were ascribed mainly to the Varicolour Clays (Argille Varicolori) formation (Createaceous-Oligocene) and to the St. Bartolomeo flysch formation (Serravalliano). Lead-coloured siltstone outcrops and pebbly mudstones, lying on the A.V. clays and limestones, and some outcrops of white sandy silts and grey silty sands, transgressive on the pebbly mudstone member (tentatively ascribed to the Messinian arenacoeus-pelitic successions), have limited extension (fig. 1). The A.V. formation successions are generally tectonically superimposed on those of the St. Bartolomeo formation, although, locally, covers of the A. V. clayey-calcareous successions on the arenaceous successions of the Irpinian Flysch were also observed.

On the pre-quaternary substratum various outcrops of cover successions were found. On the basis of their geological significance and geo-mechanical behaviour, they were divided into: colluvium deposits of U-shaped valley, colluvium talus deposits, fan deposits, and recent and present alluvial deposits. The last ones, which are the most common in the area, include without distinction also old, recent and present landslide accumulations. For a more detailed analysis of the substratum formations, of the cover successions outcropping in the area, and of the correlations between the litho-stratigraphic and litho-technical units, see Corbi & *alii* (1995), Corbi & *alii* (1996) and Guida & *alii* (1996).

In Guida & *alii* (1996), the geo-morphological configuration before the collapse of April 12, 1996 was reconstructed on the basis of the 1992 1:5.000 topographic regional technical map. Corbi & *alii* (1996), on the basis of the 1996 post-landslide air-photographs and cartography, made a detailed typological morpho-evolutional and temporal characterization of the slide movements. Lanzara & *alii* (1996) made a detailed quantitative reconstruction of the volumes involved in the 1996 landslide, based on the comparison between the 1992 and the 1996 (post-landslide) digital topographic maps. Such previous showed, for example, that many slides (single ones or phenomena linked in landslide systems, with different states of activity and evolution) were previously distributed on the slope. On April 12, 1996 one of the systems suddenly reactivated, collapsing through a complex, slide-flow type of movement (fig. 1).

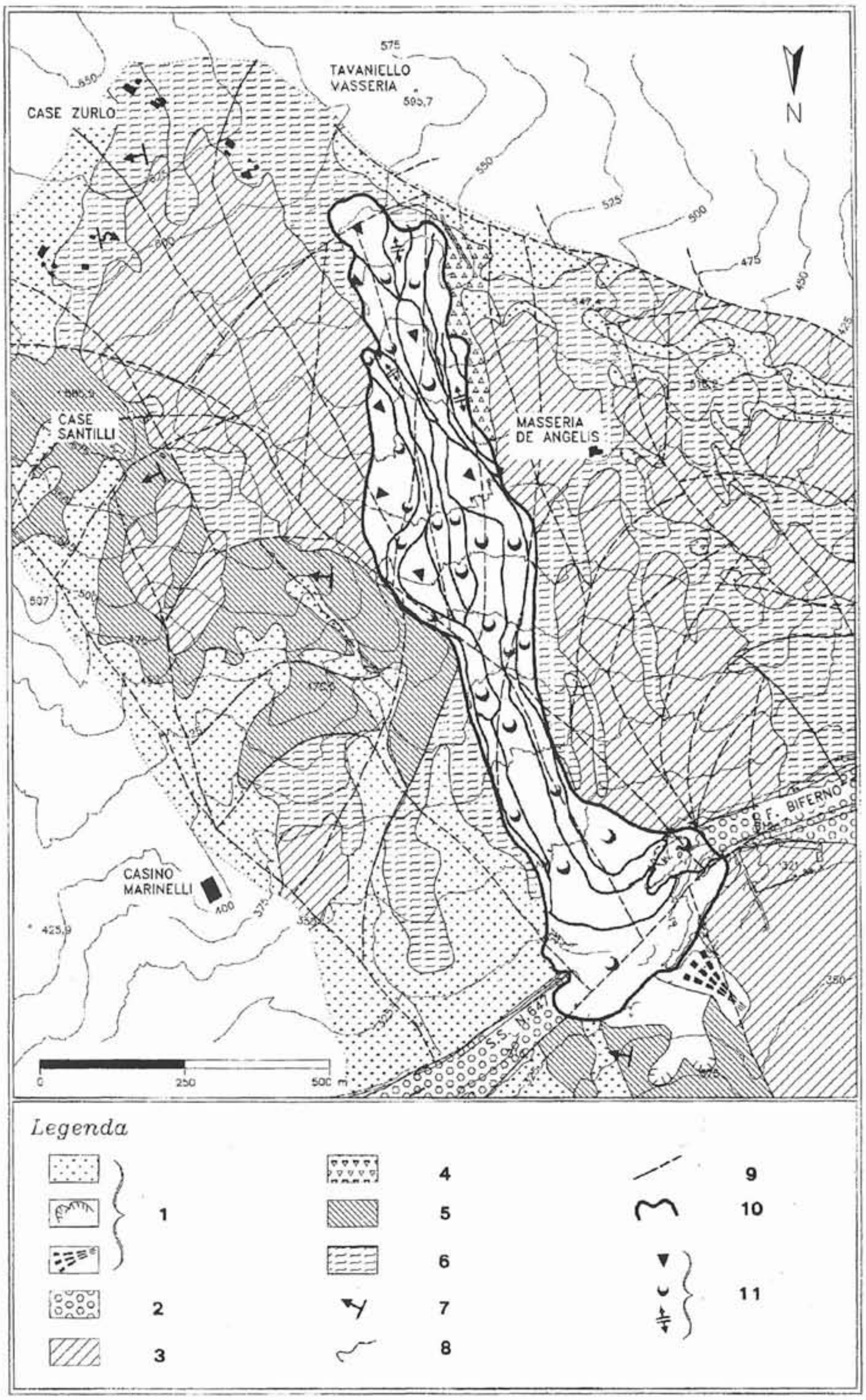
The landslide system can be subdivided into simple subsystems, with different modality and time phenomena that reactivated, so causing a chain effect, probably after the remobilization of an old rotational slide in the central zone (Corbi & *alii*, 1996) and subsequent retrogressive collapses. The considerable quantity of material moved by the flow partly filled the valley bottom and partly channelled along two main branches which partially filled the depression created by a probable old rotational slide in the central area of the Covatta valley (central block).

The heavy rainfalls that occurred in the fall-winter of 1996-97 caused, at the beginning of May 1997, a substantial general remobilization of a large part of the 1996 slide system. Towards the end of the winter of 1998, a new acceleration of the movement further modified the outline of the landslide. This movement is still active.

In this work the mid-term geo-morphological evolution of the Covatta valley, in which the landslide developed (mid-term geomorphological evolution analysis) is analyzed, comparing it with the meteorological conditions prevailing in the area since 1954.

The geo-morphological observations regarding different series (1954, 1977, 1981, 1987, 1992, 1997) of air-photographs, the analysis of the available cartography, and direct surveying allowed us to follow, in a time span of more than 40 years, the morpho-evolution of the area. The comparison between the meteorological conditions that occurred in the study area and the related morpho-evolutional phases, in a sufficiently long (1954-1997) time span, showed that the preparatory processes preceding the slide system's paroxysmic reactivation were fundamentally determined by a continuous succession of particular climatic and meteorological conditions, which led to a progressive preparation of the geo-morphological arrangement. The morpho-evolutional phases, reconstructed through multi-graded and multi-temporal air-photograph interpretation, integrated by land-use analyses, were compared with the hydrological parameters recorded in a nearby station, representative of the rainfall-temperature regime of the area examined, belonging to the Italian National Hydrographic Service (S.I.M.N.). For the last evolutional sequences preceding the collapse, we also considered the first records of the reactivation phenomenon, as decribed in technical surveys and documented evidence.

FIG. 1 - 1) Colluvium: trough-floored small valley, talus and alluvial fan; 2) Present alluvial deposits; 3) Landslide tongues; 4) Arenaceous-pelitic Terranes; 5) S. Bartolomeo Formation; 6) «Argille Varicolori»; 7) Strata attitude; 8) Stratigraphic boundary; 9) Fault; 10) Boundary of April 12, 1996; 11) Landslide typology: earth slide, earth-debris flow, lateral spreading.



THE REACTIVATION PHASE OF MAY 1997

During the fall and winter of 1996-97, the slide's mass underwent several partial movements, as a consequence of long rainy periods (Guida & *alii*, 1998). At the beginning of May 1997 a marked reactivation phase, which further reshaped the heap, created humps, sinks, cracks, tension and compression fractures, in such rapid evolution that any topographic survey was at that time impossible. The advancement of the foot of the slide progressively occluded the temporary outflow channel of the Biferno river and damaged a temporary linking stretch of highway 547, both built in the spring of 1996, forcing the reclosure of the road to traffic. In the upper area, the crown slide scarps were remodelled by a large number of roto-translational slides, whose heaps fed flow tongues converging in the valley.

The post-reactivation geo-morphological map, drawn on the topographic map derived from the September 1997 air-photogrammetric digital restitution (fig. 2), shows the configuration of the slide system in May 1997. This configuration includes depletion and flow zones (Cruden & Varnes, 1996), which can be divided as follows:

a) *Upper zone of depletion*, corresponding to the crown of the slide, where superficial slides developed, associated with flows and deep slides, which enlarged the main scarp area;

b) *Intermediate flow zone*, corresponding to the area in which the remoulded materials were carried valleywards, along the sides of the slide's main body and around the central block;

c) *Intermediate translational zone*, including the area in which multiple, consecutive roto-translational slides, with a compound rupture surface -the estimated depth is in ex-

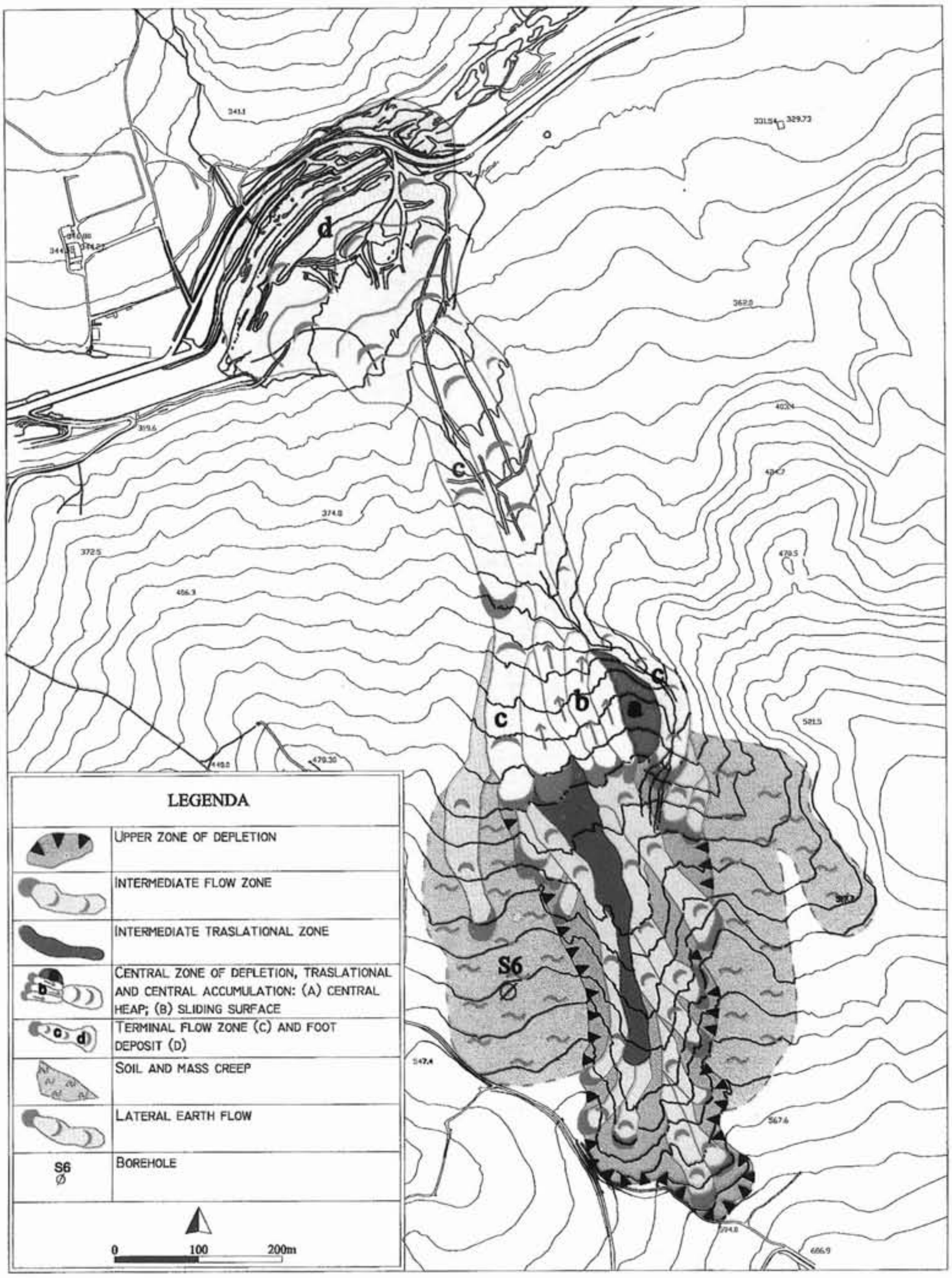


FIG. 2

cess of 15 m (Lanzara & *alii,* 1996), caused a progressive sliding of the materials valleywards;

d) *Central zone of depletion, translational and accumulation*, corresponding to the slide area in which sequences of superimposed and melted earth-debris slides/earth-debris flows developed, starting from the lower part of the central block;

e) *Terminal flow zone (a) and foot deposits (b)*, including the valley terminal area, in which the increased load remobilized the superimposed material and added new flow material.

The configuration of the evolutional phase of May 1997, as mentioned earlier, was further modified by new phases of remobilization at the end of the winter seasons of 1998 and 1999, with subsequent roto-translational slides in the crown area and along the sides, and remobilization of the accumulated materials in the mid-lower part of the landslide. These new evolutional phases show that the phenomenon, through multiple reactivations, tends to become simpler through the melting of the elementary forms which constitute the slide system, conveying the slide materials valleywards mainly by means of flow-type movements. It is important to specify, however, that the artificial removal of a considerable volume of material from the lower accumulation zone markedly altered the natural shape of the slope system's mid-lower area.

MULTI-GRADE AND MULTI-TEMPORAL AIR-PHOTOGRAPH INTERPRETATION PRECEDING THE APRIL 12, 1996, COLLAPSE

The morphological features of the Covatta valley, derived from the analysis of the air-photographs of 1954, 1977 (September 13), 1981 (July 21), 1987 (February 3) and 1992 (June 1), allowed us to follow the valley's recent morpho-evolutional stages, over a period of more than forty years.

The Covatta valley presents a wide fan-shaped head, with more developed stream channels on its left side; its terminal area meets the Biferno river with a narrow straight-course channel, whose direction (NNW-SSE) is controlled by the litho-structural arrangement. In the head zone, which is very asymmetrical, the right side is steeper and narrower than the left side. On the latter side the slide movement of April 12, 1996 developed, with a sliding direction that was almost parallel to the axis of the main channel. The wide head fan is typical of low hierarchical order hydrographic basins in structurally complex successions, where the impluvium geometries are controlled by old, recent and present mass movements, and, secondarily, by canalized erosion processes. In our opinion, the morpho-evolutional situations that were shown on the aforesaid air-photographs show the last moments of the pre-paroxysmic phase, preceding the April 1996 collapse. In the geo-morphological schemes of fig. 3 (shown here in a simplified version for typographical reasons), we have privileged the representation of land-use and of the main erosional and denudational forms concerning the years 1954 (fig. 3a), 1977 (fig. 3b), 1981 (fig. 3c), 1982 (fig. 3d), 1987 (fig. 3e) and 1992 (fig. 3f). The scheme in fig. 3g shows the area affected by the phenomenon of April 12, 1996. The observations derived from the multi-grade and multi-temporal air-photograph interpretation can be summarised as follows:

a) considerable erosional depletion took place (from at least 1954 onwards) in the head of the small valley on the left side of the Covatta valley, subsequently struck by the slide event of April 12, 1996, and corresponding to the present main scarp area;

b) the unearthing, by means of erosional and denudational phenomena, in 1987, of the NNE-SSW structural scarp in the landslide main scarp area, was partially cancelled by the April 1996 roto-translational landslides;

c) the tree cover in the valley's mid-upper area was more extensive in the 80's than in 1954;

d) at least until 1992, morphologies were strongly in relief in the intermediate area of the left side of the valley and hollow both at the head of the small valley on the left side (marked erosional and denudational depletion zone) and in the lower part of the slope (zone of depletion by rapid flows);

e) in 1987, the increase in the erosional processes and the generalized unearthing of the scarps that were longitudinally arranged on the left slope of the old gravitational phenomenon the accumulation of which (central block) diverted the main axis of the valley were noticeable; such forms, although morphologically less defined, were still verifiable in 1992;

f) a heavy valley erosion at the central block margin, downstream from the confluence zone of the two main deep valleys, was noticeable;

g) in 1987, an extensive, intense depletion, both in the head zone and in the left median area of the valley was noticeable, with evident structural and/or gravitational scarp unearthing;

h) a slow (in comparison with 1987) morpho-evolutional stage was noticeable in 1992, except in the flow depletion area, on the left side at the top of the central block;

i) in 1992, an heavy downcutting stream (without large instability phenomena on the banks) was noticeable in the bend of the stream flanking the central block on the right;

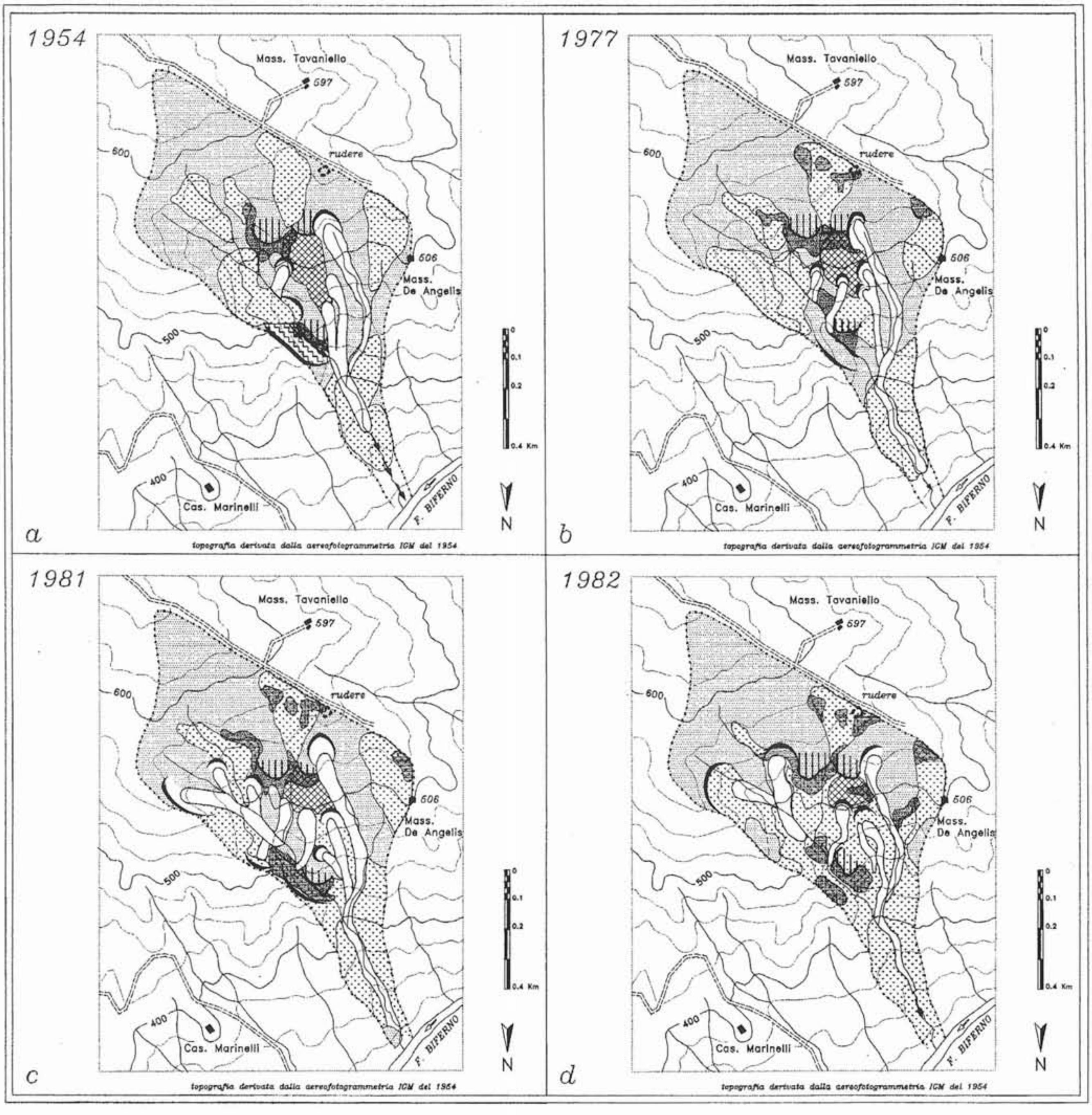
j) the rapid flows evolutional phases on the slope show a marked seasonal control;

k) the various flows (from slow to very rapid) brought about, until 1992, a considerable overall denudational effect in the mean-upper area of the slope (April 12, 1996, depletion zone).

ANALYSIS OF THE METEOROLOGICAL AND CLIMATIC CONDITIONS OF THE 1954-1997 PERIOD

General aspects

The analysis of the activation and/or reactivation of the complex landslide phenomena of the province of Campobasso (Guzzetti & *alii* 1994, 1996) seems to indicate that



(Fig. 3)

most of the gravitational movements tend to occur towards the end of winter and the beginning of spring, when the groundwater recharge of the slopes reaches the maximum level in rainy years. Because of the low permeability of the mainly pelitic structurally complex successions, the groundwater recharge occurs chiefly during long periods of rain and in conditions of low potential evapotranspiration.

Since on these successions the correlation between a single pluviometrical event and an instability phenomenon affecting the slopes is not generally a direct one, especially with regard to wide and deep slide phenomena (Cascini & *alii*, 1986), it is plausible that the immediately preceding pluviometrical events do not play an important role in determining the activation of a large sliding movement such as

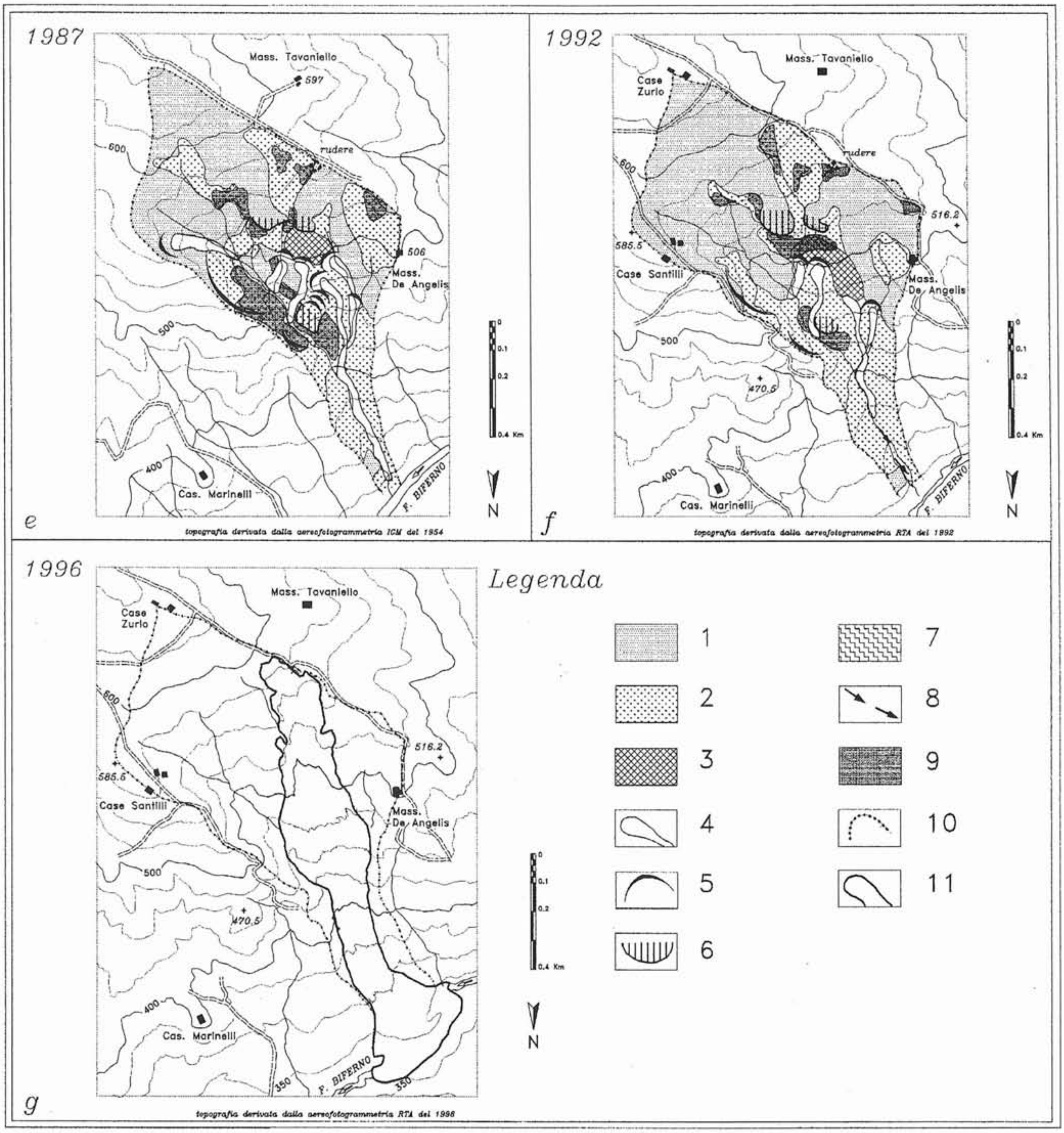


FIG. 3 - 1) Denudation area of ancient and (partly) recent gravitative slope phenomena. Active phenomena: soil, mass and deep creep. Landuse: dry sown fields; 2) Denudational area of dormant earth-slide/earth-flow phenomena. Active phenomena: small earth slide/earth-debris flow. Landuse: uncultivated; 3) Source area of active rapid earth-debris flow; 4) Boundary of flow/accumulation area of active rapid earth-debris flow; 5) Ancient or recent landslide scarp, somewhere influenced by structure; 6) Erosional bench delimited by steep scarp. The lowest altitude is on the recent landslide body (central heap); 7) Fluvial erosion area with rills and gullies; 8) Downcutting stream; 9) Forest; 10) Watershed; 11) April 12, 1996, landslide boundary.

that of April 12, 1996. The influence of rainfall on this phenomenon needs to be studied in the more complex context of a progressive increase in the pore pressures due to particularly humid seasons, which was the determining factor in a context of progressive weakening of the slope, subject to a long phase of remarkable modelling due to mass and channelized erosion phenomena (slope's preparation phase).

Hydrological analysis methodologies

In order to determine correctly the role of pluviometrical phenomena in determining the stability of the slopes characterized by low permeability, the best instruments of analysis, apart from the infiltration process model (whose application here would have been exceedingly complex because of the heterogeneity of the morphological and geostratigraphical conditions and the lack of any long term measurements of piezometric levels, of surface runoff flow rates, etc.), is the soil water balance, carried out by means of the Thornthwaite & Mather (1957) method and the analysis of the cumulated rainfall curve. The analysis and comparison of the data obtained by means of these methods make it possible to determine, on a time scale of several decades, the most favourable periods for the slope morpho-evolutional processes.

The hydrological data considered here are the rainfalls and the daily temperatures concerning the same period of time as the one considered for the reconstruction of the morpho-evolutional stages (1954-1997). Because of the lack of spatial correspondence between rain and thermometric stations, data from different stations had to be used. The daily rainfall values at the Castropignano station (700 m above sea level), consisting of only a «simple» rain-gauge, were analyzed. This station can be considered the most representative of the rainfall regime of the Covatta valley because of its altitude, vicinity (less than 5 km to the W) and conditions of exposition. The daily temperatures, on the other hand, were obtained from the Campobasso station, at 686 m above sea level and at about 9 km to the SE.

The soil water balance with the Thornthwaite & Mather (1957) method, as is well known, makes it possible to estimate, on a monthly scale, the rain distribution in terms of atmospheric losses (*actual evapotranspiration = Er*), of soil water storages, such as retained waters (*field water capacity = Cr*), and of available water resources in terms of a presumed global water surplus (D) (*effective infiltration and surface runoff*). Such an analysis of rainfall data allows an evaluation, although only on a monthly basis, of the hydrological conditions which favour the groundwaters' recharge.

Although this method does not enable us to separate quantitatively the actual infiltration from the surface runoff, the calculation of the presumed global discharge and of the soil water storage provides sufficient indications regarding the modalities of runoff and of groundwater recharge which generally control the main morpho-dynamic processes (Brundsen & Ibsen, 1994).

The field water capacity was calculated in relation to the soil texture and to the landuse, through the tables of reference proposed by the above mentioned method. The soil texture of this area is, on the average, clayey-silty (U.S.D.A. triangular diagram), while the cultivation, in the studied period, was of the dry sowing type in 45% of the valley; the remaining areas of the valley were uncultivated (35%) and subordinately covered by forest (20%). In relation to root development in terms of depth for these types of land-use on a clayey-silty soil, we have a field water capacity of respectively 70 mm, 110 mm and 180 mm. Thus, a field water capacity value derived from the weighted mean of the previous values, equal to about 100 mm, was adopted. Although land-use varied considerably during the period analysed (fig. 3), the adoption of a constant value was considered sufficiently significant.

The cumulative rainfall for a given period of time represents the hydrological parameter which best characterizes the hydrological conditions that are important for the stability of a slope. It is indicative both of the overall rainfall and of the average rainfall intensity. These factors can play different roles in determining in the groundwater recharge, according to the conditions of permeability and local stratigraphic situations. From the values of the cumulative rainfall over a given period of time and the indications of activation of instability phases, a threshold value can be established, beyond which the probability of slide phenomena occurring increases (Crozier, 1996). This allows us to devise statistical hydrological models which provide indications about the probability of occurrence of instability phases (among others, Campbell, 1975; Caine, 1980; Crozier & Eyles, 1980; Govi & *alii*, 1984; Cancelli & Nova, 1985; Sirangelo & *alii,* 1996). The time «window» in which the cumulative rainfalls prove to be more critical generally depends on the typology of the slide phenomena (shallow or deep). Shallow slides are affected by the cumulative rainfalls over short periods of time, while deep phenomena are affected more by cumulative rainfalls over long periods of time. The former case is related to the saturability of the generally more permeable soils; the latter case to the saturability of deeper, less permeable soil or rock masses. Obviously, the saturation of a superficial layer occurs in a relatively short time, if the saturation front rises from bottom to top, starting from the interface with an underlying less permeable material (hortonian model); in the case of a deeper soil or rock mass, on the other hand, the increase of pore pressures, related also to the local hydrogeological context, occurs over a longer period of time. Moreover, in a complex morpho-evolutional context and in low permeability successions, such as those of the valley studied, the cumulative rainfalls can provide useful information about surface runoff flow rates and about the periods in which the channelled erosion phenomena are more intense.

Analysis of the historical hydrological series and of their possible relationship with the morpho-evolutional stages

We analyzed the historical series of the daily rainfalls and temperatures for a period of more than forty years (1954-1997). The analytical approach consisted in the calculation of the water soil balance on a monthly base for the whole period examined (figg. 4, 5) and, for the last ten

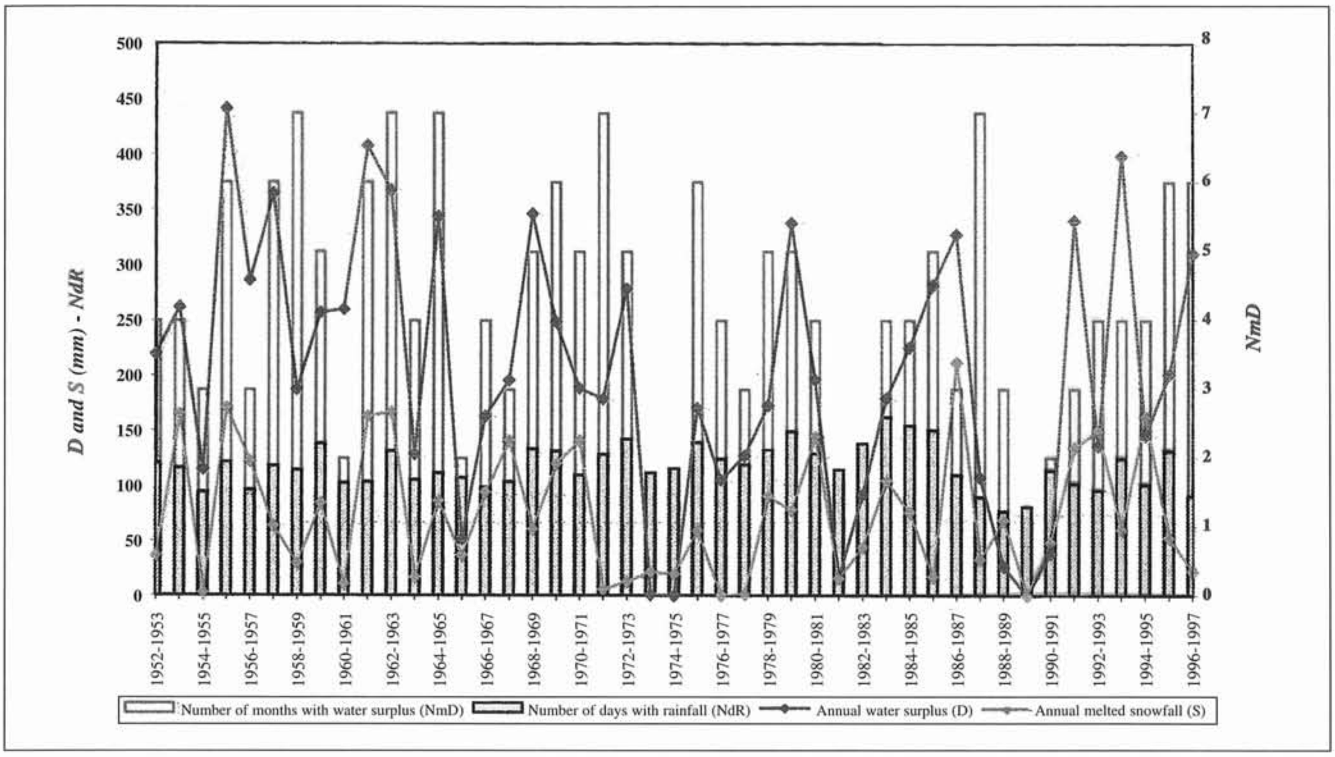


FIG. 4 - Concise data on the soil annual water balance in the period 1952-1997. Besides the annual water surplus (D) other hydrological factors governing the effective infiltration are put in evidence: number of months with water surplus (NmD), number of days with rainfall (NdR), and snowfall (S) expressed in mm of equivalent rainfall.

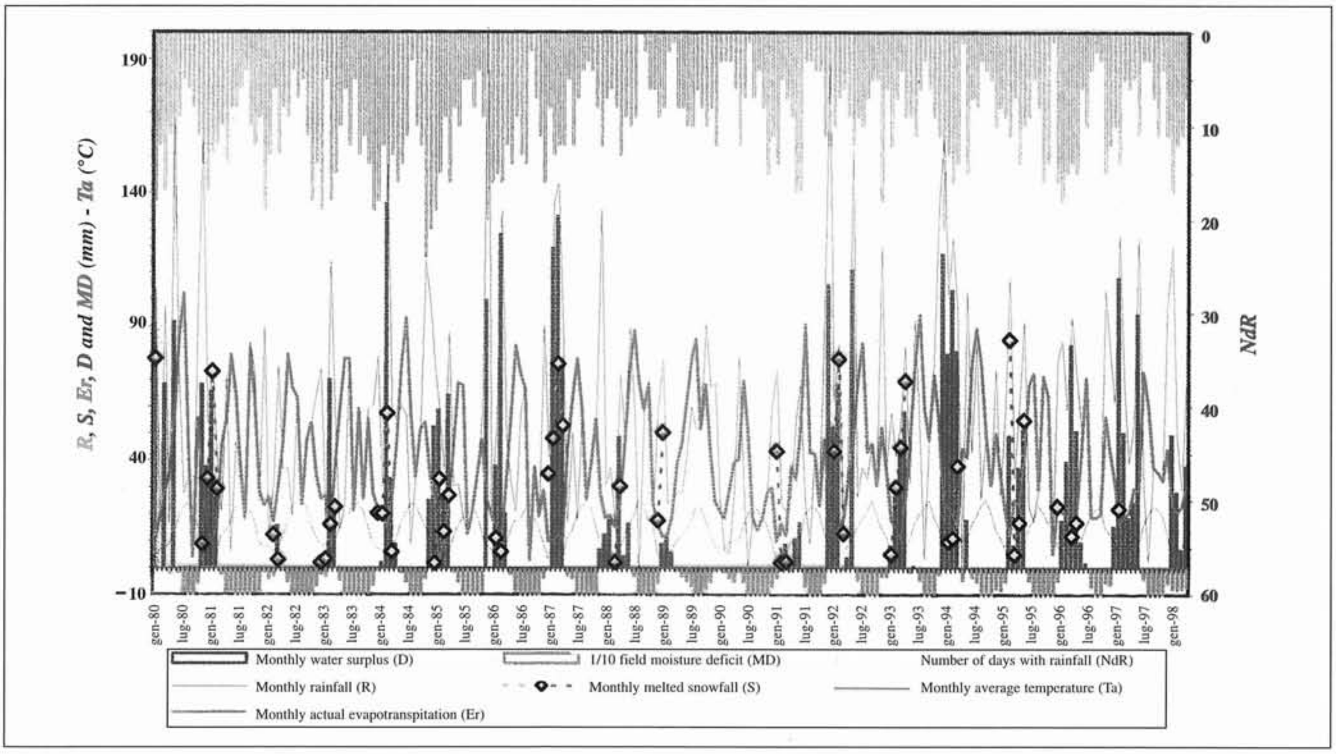


FIG. 5 - Monthly soil water balance in the period 1980-1998. All utilised hydrological factors, the monthly number of days with rainfall (NdR) and the snowfall (S) are expressed in mm of equivalent rainfall and put in evidence. The field moisture deficit (difference between soil water supply and field water capacity, extimated 100 mm) has been graphically reduced by a factor of 10.

years, also in the analysis of the daily rainfalls through cumulative curves, both progressively and over a period of 120 days (figg. 6, 7). This last analysis focussed on on the period in which the succession of climatic events was more important for the morpho-evolution of the valley. In both analyses particular attention was paid to snowfalls, the melting of which contributed significantly to the resulting infiltration processes, although seldom more so than the rainfall intensity.

Among the parameters derived from the soil water balance, only those representative of water capable of a morpho-dynamic action were considered, namely runoff and actual infiltration. The parameters calculated concern the water surplus, the number of months per year with water surplus and the number of rainy days (daily $P > 0$ mm).

From the analysis of the data, summarised per hydrologic year in fig. 4, it is immediately evident that the yearly water surplus (i.e. the availability of water resources that contributes each year to morpho-evolution), varied in the period considered from 0 to 450 mm, with an average value of about 205 mm/year (variation coefficient = 58%). In the same period the rainfall values were between 366 mm and 938 mm, with an average value of 673 mm (coefficient of variation = 19%). It is evident that the water surplus has a greater variability than that of rainfall, obviously also due to the evapotranspiration regime and, therefore, to the annual temperature variations. Moreover, it is possible to infer a dominant cyclical variation, characterized by a period of about 7 years.

Considering the morpho-evolutional stages, as reconstructed by means of the analyses of the air-photographs and of the data derived from chronicles, it is possible to divide the temporal sequence studied into three different evolutional stages. Notwithstanding the lack of temporal homogeneity of the data, instantaneous for the air-photographs and continuous for the climatic data, a relationship between morpho-evolutional stages and climatic conditions can be established and can provide useful indications about the valley's morpho-genesis, in the period that preceded a given series of air-photographs. The stages that have been recognized are the following:

– the first stage, corresponding to the 1954-1977 period, is the one about which we only have morpho-evolutive information concerning the beginning and the end of the period. The geo-morphological conditions of 1954 can neither be compared to any preceding configuration, nor connected with the preceding meteo-climatic events. However, since the hydrological year 1954-1955 is characterized by low water surplus values (equal to about 125 mm), no snowfalls and only three months with water surplus limited to three, the geo-morphological processes shown by the air-photographs can be attributed to the climatic characteristics of the immediately preceding hydrological years. In the long period that followed, until 1977, a large number of very humid hydrological years were recognized. Many of of them were characterized by above average water surplus values, and distributed over long sequences of months; the succession displays two significant relative minimum levels, relating respectively to the year 1963-1964 and to the two-year period 1973-75, when the water surplus was absent (fig. 4). The geo-morphological analysis of the 1977 air-photographs shows an evolutional stage not very different from that of 1954. This phase (with respect to the overall period of time that has been considered), although characterized by a succession of years with considerable water quantities, both in the form of surface runoff and effective infiltration, and also with significant snowfalls, does not display the occurrence of rapid evolution processes. During this period the geo-morphological arrangement, probably, undergoes a «tensional recharge», and seemingly shows a good resistance to climatic «stress».

– the second stage (1977-1993) is characterized by a larger quantity of morpho-evolutional information sources, provided in particular by the aerial photographs of 1981, 1982, 1987 and 1992. The hydrological years between 1977 and 1981 show an increasing water availability, from a minimum in 1974-1975 in the first stage, to a maximum in 1979-1980, with a water surplus of about 340 mm, distributed over a five month period (fig. 4). The following hydrological year, although with a lower availability of water, was characterized by higher snowfall values, distributed over a four month period (figg. 4, 5, 6). Subsequently, in the year 1981-82, another minimum was reached, with a water surplus of about 20 mm only. The «intensity» of the denudational processes that was shown by the aerial photographs of 1981 and 1982 can therefore be related to the meteo-climatic conditions of the preceding years. After 1982, another meteorological and climatic cycle, with a duration of about seven years, was recognized. Its apex was in the hydrological year 1986-1987, which was characterized by a water surplus of about 310 mm and, above all, by the highest snowfall value (about 200 mm) in the overall historical series. In the years 1988-1989 and 1990-1991 the water availability was once again scarce, with a maximum water surplus of 30 mm. The very strong increase in the erosional and denudational phenomena shown by the aerial photographs of February 3, 1987 (also in the nearby valleys, such as «Fosso Tonnella») can probably be ascribed to the considerable water availability, especially in the form of actual infiltration due primarily to the unusally heavy snowfalls. On the other hand, the morpho-evolutive standstill shown by the aerial photographs of June 1, 1992, seems connected to the preceding dry hydrological years, even though the hydrological year 1991-1992 had a significant water availability with about 325 mm of water surplus. It is probable that in this stage the meteorological and climatic conditions induced a preparatory morpho-evolution of the 1996 collapse, «weakening» the slope and making it more vulnerable to future stress conditions.

– The third stage, 1992-1997, is characterized by hydrological events that were decisive for both the collapse of the spring of 1996 and the reactivation of the landslide in the spring of 1997. In this period the meteo-climatic conditions were characterized by a tendentially increasing water availabilty, with an absolute maximum in the year 1993-1994, followed by a relative minimum in the hydrological year 1994-1995, and then again by the an increase until the year 1996-1997. Among the most significant meteorological events in this period, we would draw attention to the very intense rainfalls of the winter of 1993-1994, whose importance can be appreciated if we consider both the sharp slope increase of the progressive cumulative curve and the cumulative value for 120 days of about 500 mm (fig 7), the highest value of all the historical series examined. The only reference to these rainfall events seems to be a technical report by ANAS (the Italian National Highways Agency) of February 14, 1994, concerning the unfavourable geomorphological and hydrogeological conditions (lit. *dissesto idrogeologico*). These conditions surveyed in the Covatta valley, together with the strong erosion of its talweg, were such as to threaten a pillar of the «Pozzillo» viaduct of highway 647, in the Biferno river valley bottom. Successively, in 1994-1995, considerable snowfalls (equal to 150 mm) of equivalent rain occurred again, concentrated in few days during January and March-April (fig. 7). It snowed for respectively 85 mm of equivalent rain in January (avg. melted rate 4,5 mm/day), 17 mm of equivalent rain at the end of March (avg. melting rate 10 mm/day), and 55 mm of equivalent rain in April (avg. melted rate 14 mm/day). And precisely in this period, from April to June of 1995, some reports from the Prefecture of Campobasso and ANAS indicated the presence of considerable deformations of the Covatta valley slope, again threatening the «Pozzillo» viaduct of highway 647. The hydrological year 1995-1996, although not characterized by high values of water availability, had a particularly homogeneous distribution of rainy days, resulting in a water surplus for 6 consecutive months (figg. 4, 5). Such conditions, expressed by the correlation coefficient of the progressive cumulative curve (R^2=0.9942, the maximum value of all the hydrological years of the historical series considered), was certainly very favourable to the processes of actual infiltration. In the spring of 1996 the landslide system reached its phase of paroxysm, with the general collapse of the slope. Again in the following hydrological year there was a remarkable water availability, with about 300 mm of water surplus, distributed over a period of 6 consecutive months (figg. 4, 5). In the spring of 1997 and in February 1998, two violent reactivation phases mobilized a large part of the landslide and tended to modify the arrangements of the phenomenon.

The influence of meteorological and climatic factors on the slope's final morpho-evolutional stage seems to be very marked. Indeed, the abundant rainfalls of the winter 1993-1994 probably further «weakened» a slope that could already be considered unstable due to the meteoric events of the year 1986-1987, increasing the erosional processes connected with the central block and amplifying the denudation processes towards the top of the slope, in the flow depletion areas.

Moreover, the considerable water surplus certainly also determined an increase in the pore pressures in the deeper parts of the slope.

Subsequently, the snow melt at the beginning of 1996, concentrated in particular in the month of April, is also likely to have caused a final pore pressure increase beyond a threshold value that is critical for the stability of the slope.

CONCLUSIONS

The correlation between the reconstructed morpho-evolutional sequences and the meteorological data highlighted the fact that the rainfalls that occurred in the period 1954-1992 produced morpho-dynamic effects of different intensity. For instance, the acceleration phases of the denudational processes, which in the winter 1986-1987 involved large areas of the valley, are clearly a «reaction» to the intense rainfalls and snowfalls of that period. The slowing down of the development of the processes, which was appreciable in 1992, was caused by the very limited water availability of the three previous years (1988-1989, 1989-1990 and 1990-1991). Nevertheless, it is fairly clear that the «morphodynamic reactions» are delayed with respect to the meteorological events, in relation also to their intensity. For example, the rainfalls that occurred in the year 1991-1992, although significant, provided a negligible acceleration in the rate of movement of the flows that were so «active» in 1987, as can be seen from the 1992 air-photographs. Such «inertia» could be attributed to the fact that the probable stress increases, in low permeability successions, generally occur over a long period, on a pluriannual scale. Within this model, the accelerations in the morpho-evolutional processes, observable in the years 1986-1987 and 1995-1996, can be related to the maximum rainfall values of a globally rainier period. In these hydrological years the melting of snow could also have played a particularly significant role in the equilibrium of the slope, by contributing directly to the rise of groundwater.

In the light of such considerations, it is evident that the correlation between single pluviometrical events and deep landslides is a particularly complex one. This is especially true if one considers, in simplistic terms, that the triggering of a landslide phenomenon is linked only to the reaching of a precipitation threshold value. As a consequence, it is very difficult to determine, either spatially or temporally, the hazard due to landslide systems, whose activation and/or reactivation seems to be linked more to a hydro-geomorphological history than to a single precipitation event, remarkable as it may be. From the case presented here, for example, it is possible to hypothesize that complete slope failures occur at the end of long evolutional phases of progressive «weakening» of the system and, consequently, also as a result of a decrease over time in the rainfall threshold value.

The shaping of slopes on structurally complex successions should therefore necessarily include both preparatory evolutional stages, with erosional and denudational phases with relatively moderate effects, and acceleration phases of the morpho-evolutional processes, with catastrophic effects. The preparatory phases, generally rather long, *weaken* the slope, preparing it for complete failure. It is impossible to state how long these phases can last. Experience gained in the complex geological and geo-morphological context of the central and southern Apennines and the study of this phenomenon allow us to suppose that the preparation stage, preceding the complete failure phase, requires times of the order of at least several decades. On

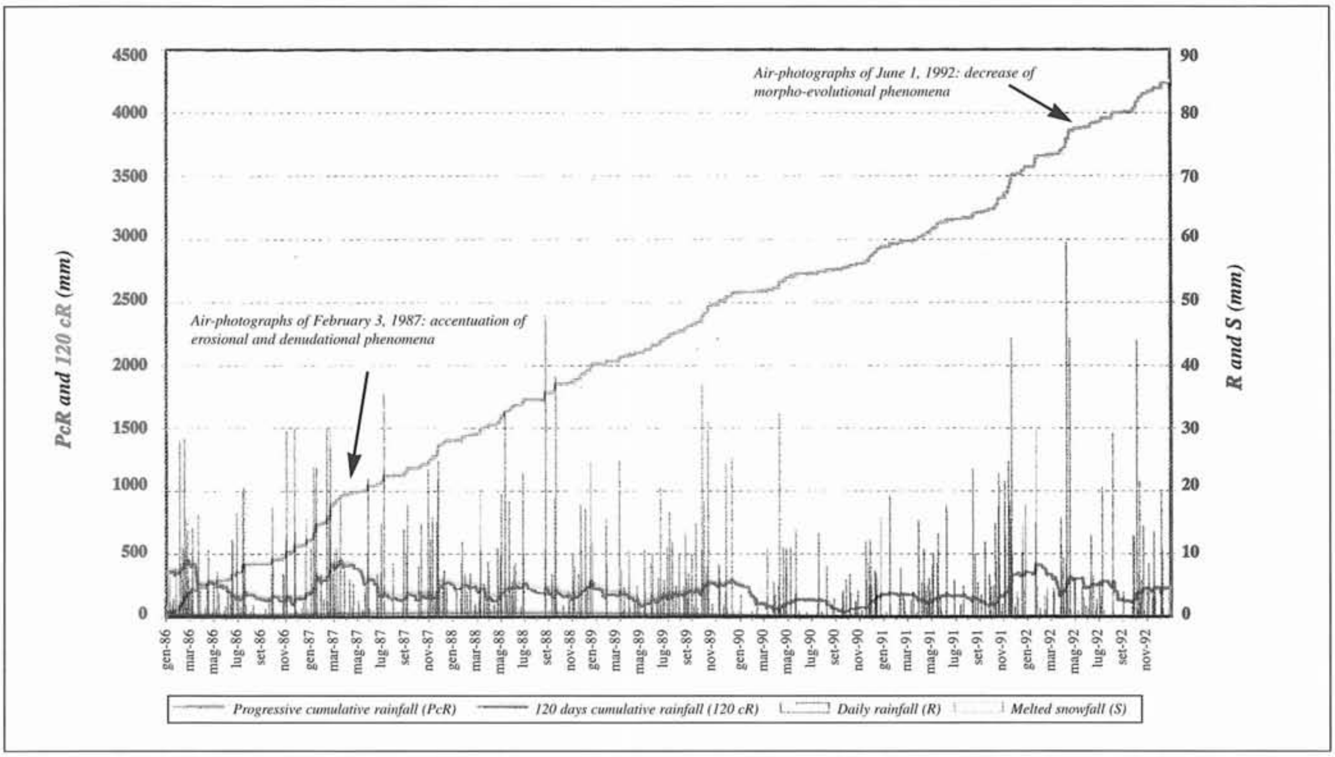


FIG. 6 - Daily precipitations recorded at the Castropignano rain gauge station (700 m a.s.l.) in the 1986-1992 period, distinguished in rainfall (R) and snowfall (S), progressive cumulative rainfall (PcR), and 120 days cumulative rainfall (120cR).

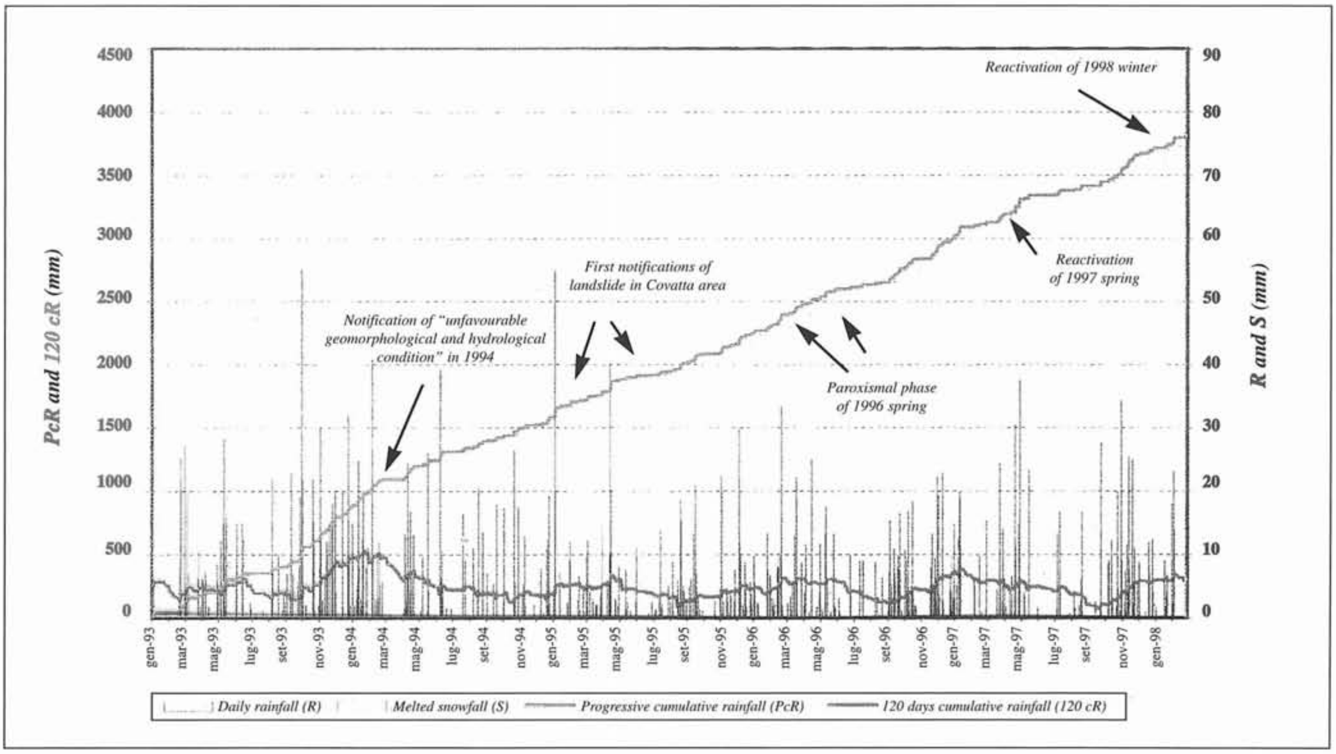


FIG. 7 - Daily precipitations recorded at the Castropignano rain gauge station (700 m a.s.l.) in the 1993-1998 period, distinguished in rainfall (R) and snowfall (S), progressive cumulative rainfall (PcR), and 120 days cumulative rainfall (120cR).

the other hand, the activation/reactivation of single landslide phenomena, especially the shallower ones, is closely related to the increments in water surplus, with return times of only a few years. It is evident that if other factors of instability, such as the action of man, seismic stress and so on, are added to the meteorological factor, the preparation phase for complete failure is accelerated.

The geological and geo-morphological analyses of the air-photographs and of the available cartography, as well as the sistematic field surveying, together with the statistical analysis of the historical meteorological data, allow some reliable hypotheses about the future evolution of the April 12, 1996 landslide:

a) the phenomenon will tend to simplify and become visually uniform, by means of a progressive homogeneization of its simple components, with the features that are typical of an earth-debris flow;

b) by retrogressive evolution of the main scarp and of the sides, tension cracks will initially open up and, successively, slides will start;

c) the sliding materials from the main scarp and the sides will tend to remould completely and flow rapidly;

d) the materials of the single flows will tend to homogeneize, because of continuous feeding from above.

This projection regards the landslide area's short and mid-term evolution, but our field observations indicate probable failures of the wide bordering areas of the current zone of depletion (fig. 2). On both the right and left side of the upper part of the landslide several crack systems, longitudinally and transversely arranged, show the development of a pre-failure phase. It is likely that the sliding of more or less extended side areas, feeding other material to the terminal flow, will inevitably cause progressive advancements of the foot deposits in the Biferno river talweg, due also to the large volume of landslide materials currently present in the central flow channel. At present, there are two hypotheses regarding the landslide area's future devolpment are two: a) remobilization of only the currently dormant landslide heap, with a total volume of some tens of thousands of cubic metres (minimal hypothesis); b) simultaneous general sliding failures of those areas (on the right and left of the upper part of the current landslide) which at present seem to be in a pre-failure phase, with expected volumes of about 7-800,000 mc (catastrophic hypothesis).

With the availability of new data (structural, geomorphological, geotechnical, etc.), short and long-term analyses of geomorphological evolution will be performed in this area, aimed at providing further details on the slope's future evolutional phases (preparation-failure-reactivation).

Based on the results of the studies that have been carried out so far, by means of the reconstruction of the past mid-term evolutional sequences of this landslide system, and thanks also to the research experience gained in recent years in other areas of the Apennines, we believe that flow phenomena play a very significant role in the evolution of slopes in structurally complex successions. In these successions it appears that a constant element contributing to the recognition of unstable slopes is the early presence of diffused earth-debris flows, with forms and evolutional features that are evidently very dependent on local situations. The continuous denudational action of these flows produces significant mid-term effects during the geo-morphological system's preparation phase, with consequent «weakening» of the slopes involved.

As well as being precursory signs of failure phases, the flow phenomena also play an important role during the terminal phase of the evolution of landslide systems, when these tend to become simpler as a result of the coalescence of the forms which constitute them. During this evolutional phase the remoulded and «homogeneized» landslide material is conveyed towards the valley bottom through flow phenomena, which perform the task of completing the emptying of the area of such landslide systems.

REFERENCES

BARANELLO S., BRUNO F., GUIDA M., LANZARA R., LIONETTI C., PERRIELLO ZAMPELLI S., SALZANO G., SCAPILLATI N., TORRE M., VALLARIO A. & VECCHIARELLI C. (1995) - *I centri abitati instabili del Molise: censimento e analisi preliminare dei fenomeni franosi*. Geol. Tecn. & Amb., 4/94, pubbl. n° 1306 del GNDCI, 5-17.

BRUNO F., LANZARA R. & VALLARIO A. (1994) - *Ambiente fisico ed evoluzione dei versanti nelle coltri molisane: il bacino del torrente Ingotte (F. Biferno)*. Geol. Tecn. & Amb., 4/94, pubbl. n° 978 del GNDCI, 5-14.

BRUNSDEN D. & IBSEN M.L. (1994) - *The temporal causes of landslides on the South coast of Great Britain*. Temporal occurence and forecasting of landslides in the European Community; European Community Program EPOCH Final Report, pp. 339-383.

CAINE N. (1980) - *The rainfall-intensity duration control of shallow landslides and debris flows*. Geogr. Annaler, 62, 1-2, 23-27.

CAMPBELL R.H. (1975) - *Soil slips, debris flows, and rainstorms in the Santa Monica mountains and vicinity, southern California*. U.S.G.S., Professional Paper 851.

CANCELLI A. & NOVA R. (1985) - *Landslides in soil and debris cover triggered by Valtellina (Central Alps-Italy)*. Proc. IV Int. Conf. and Field Workshop on Landslides, Tokyo.

CASCINI L. & VERSACE P. (1986) - *Eventi pluviometrici e movimenti franosi*. Atti 16° Congr. Naz. di Geotecnica, Bologna, 171-184.

CORBI I., GUIDA D., GUIDA M. & VALLARIO A. (1996) - *La frana in località Covatta nel bacino del Biferno (Molise): Aspetti geologici e geomorfologici*. Atti Conv. Int. «La prevenzione delle catastrofi idrogeologiche: il contributo della ricerca scientifica», Alba (CN), 5-7 Nov., vol. I, pubbl. GNDCI n° 1600, 1998, 477-491.

CORBI I., GUIDA M., TETAMO G. & VALLARIO A. (1995) - *Considerazioni sul rischio a franare di aree campione nel bacino del Fiume Biferno (Molise)*. Mem. Soc. Geol. It., 45, 1-17.

CROZIER M.J. & EYLES R.J. (1980) - *Assessing the probability of rapid mass movement*. III Australian-New Zealand Conf. on Geomechanics, vol. 2.

CROZIER MJ (1996) - *The climate-landslide couple: a Southern Hemisphere perspective*. Palaeoclimate Research, European Science Foundation, (Special Issue) 12, 329-350.

CRUDEN D.M. & VARNES D.J. (1996) - *Lanslide Types and Processes*. In: «Landslides, investigation and mitigation». Transportation Research Board, Special Report n° 247, National Research Council, Washington, D.C. 20418, 36-75.

GOVI M., MORTARA G. & SORZANA P.F. (1984) - *Eventi idrologici e frane*. Geol. Appl. Idrogeol., 18 (3).

GUIDA D., GUIDA M. & VALLARIO A. (1996) - *Analisi preliminare della frana del 12 aprile 1996 in località Covatta nel bacino del Biferno (Molise)*. Geol. Tec. & Amb., 2/96, pubbl. n° 1371 del GNDCI, 23-39.

GUIDA D., IACCARINO G. & PERRONE V. (1988) - *Nuovi dati sulla successione del flysch del Cilento nell'area di Monte Centaurino: relazioni tra unità litostratigrafiche, unità litotecniche e principali sistemi franosi*. Mem. Soc. Geol. It., 41, 299-310.

GUIDA D., GUIDA M:, LANZARA R. & VALLARIO A. (1998) - *La frana in località Covatta di Ripalimosani (CB) del 12 Aprile 1996: aspetti generali e fasi evolutive*. Quarry & Construction, 1/98.

GUIDA M. & IACCARINO G. (1984) - *Evoluzione dei versanti e franosità*. In: «Lineamenti di Geologia Regionale e Tecnica», Ricerche e Studi Formez, 75-98, Napoli.

GUZZETTI F., CARDINALI M. & REICHENBACH P. (1994) - *The AVI Project: A bibliographical and archive inventory of landslides and floods in Italy*. Env. Management 18, 4, 623-633.

GUZZETTI F., CARDINALI M. & REICHENBACH P. (1996) - *Map of sites affected by landslides or floods - The AVI Project*. CNR-GNDCI, Pubbl. n° 1346, map at 1:200.000 scale.

LANZAFAME G. & TORTORICI L. (1976) - *Osservazioni geologiche sul medio e basso bacino del F. Biferno*. Geol. Romana, 15, 199-222.

LANZARA R., PERRIELLO ZAMPELLI S.,VIGGIANI A.S. & VALLARIO A. (1996) - *La frana in località Covatta nel bacino del Biferno (Molise): Analisi tridimensionale quantitativa*. Atti Conv. Int. «La prevenzione delle catastrofi idrogeologiche: il contributo della ricerca scientifica», Alba (CN), 5-7 Novombre, vol. I, pubbl. GNDCI n° 1600, 1998, 453-462.

SERVIZIO GEOLOGICO D'ITALIA (1970) - *Carta Geologica d'Italia alla scala 1:100.000, Foglio 162: «Campobasso»*, Roma.

SIRANGELO B., IRITANO G. & VERSACE P. (1996) - *Il preannuncio di movimenti franosi innescati dalle piogge. Valutazione della probabilità di mobilitazione in presenza di indeterminatezza nell'identificazione del modello FlaIR*. Atti XXV Conv. Idraulica e Costruzioni Idrauliche, Torino 3, 378-391.

THORNTHWAITE C.W. & MATHER J.R. (1957) - *Instructions and tables for computing potential evapotraspiration and the water balance*. Pubbl. Clim. Drexel Inst. Technol., 10.

VALLARIO A. (1992) - *Frane e territorio. Le frane nell'evoluzione dei versanti e nell'uso del territorio*. Liguori, Napoli.