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INTRODUCTION

The phenomena of slope instability and floods have long been a constant feature in this study area in southern Italy, south-east of Naples (Figure 1). Earthquakes and meteorological events, in this part of the Apennines have been the main triggering factors for landslides, which have often resulted in dreadful economic and human losses. Indeed, the area was hit by an earthquake (M = 6.8) on 23 November 1980 that triggered many large landslides.

A number of geological, geomorphological, hydrological and geotechnical features of the study area have been examined in detail (EEC, 1996) and this work examines climate/landslide density relationships and the resulting changes from the 1980 earthquake.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The outcropping lithofacies can be divided into three types, shown in Figure 1 (Polemio, 1997; Agnesi *et al.*, 1982).

- Alluvial deposits (Pleistocene - Holocene) are found along the course of the Sele River and its main tributaries and are not relevant to landslide phenomena;
- Mainly clayey-marly and clayey-marly-arenaceous flysch, shales, marls, cherty limestones, sandstones and varicoloured clays (Upper Cretaceous-Palaeocene); detrital and breccia deposits of rockfall or scree (Quaternary) outcrop secondarily at the foot of the carbonate relief;
- Limestones, dolomitic limestones and dolomites (Triassic-Cretaceous) constitute the relief.

The two slopes of the upper valley of the Sele River exhibit a different hydrographic system. On the right side, the system is made up of a few channels which follow tectonic lines and display a modest evolution whereas, on the left side, deep incisions run parallel to the maximum slope line and are subject only to slight evolution. There are two detectable hydrogeological units: Mounts Polveracchio-Rainone (on the west side) and

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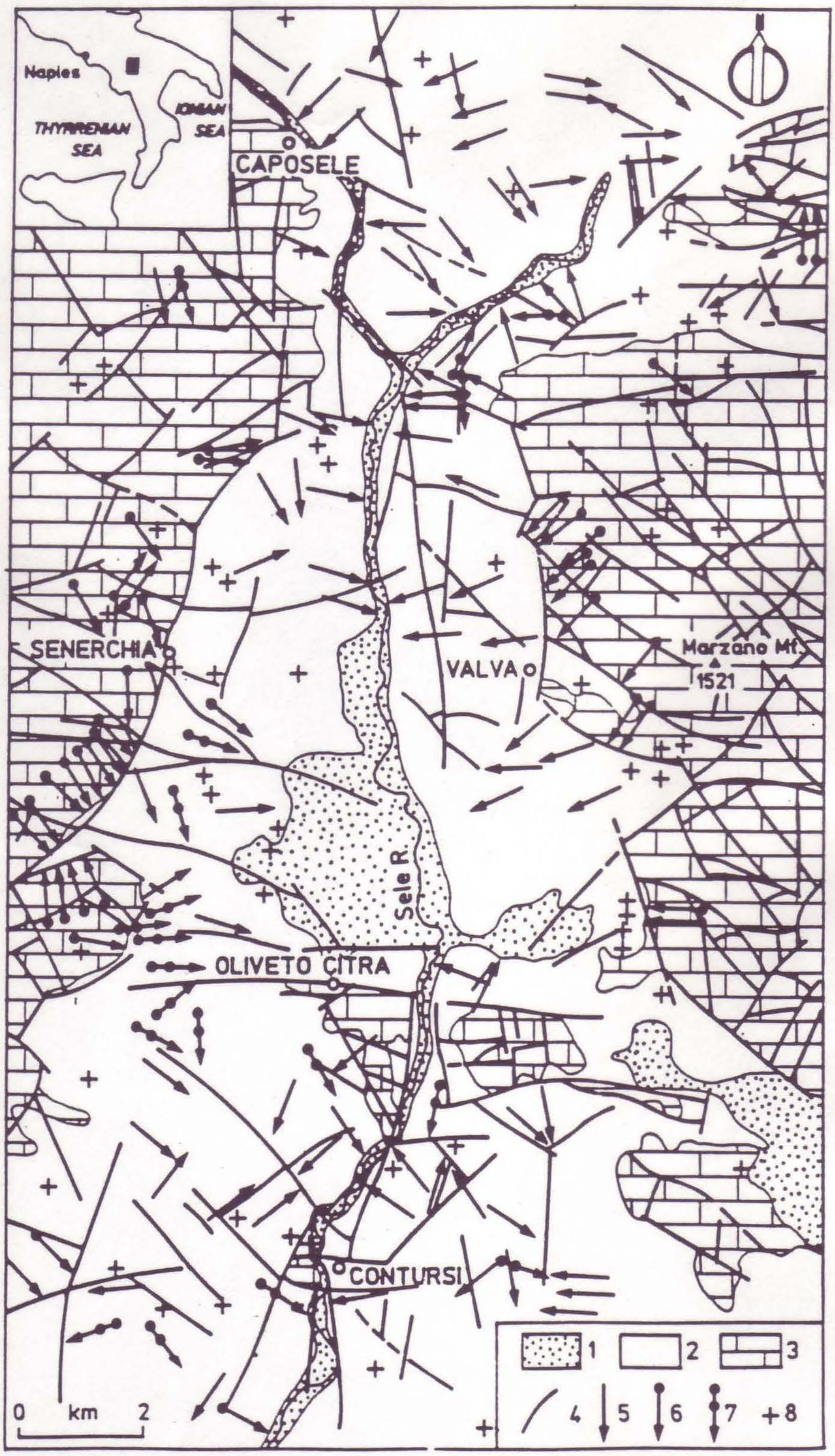

Figure 1 Schematic map of the geology, hydrogeology and morphology of landslides (after Agnesi *et al.*, 1982; Polemio, 1997): (1) alluvial deposits, medium relative primary permeability; (2) clayey-marly flysch with calcareous, arenaceous or calcareous-marly interbeds or blocks, very low to low relative primary permeability, medium secondary permeability; (3) limestone, dolomitic limestone, dolomite, of medium to very high relative secondary permeability due to fracturing and karstification; (4) landslides before 1980; (5) landslides since the 1980 earthquake; (6) type 4 and 5 landslides; (7) fault; (8) spring.

Mounts Ogna-Marzano (Budetta *et al.*, 1988), which are formed of carbonate rock. Moving towards the valley, the carbonate mass, divided into separate sheets by the tectonic activity, underlies the impervious flysch for some hundred metres. Some of these sheets are uplifted and almost surface, so that some springs are formed.

The role of an impervious limit, played by the flysch, does not improve the slope's stability (Polemio, 1997). As discussed later, this might account for the way and the extent to which the water cycle has affected landslide propensity since the 1980 earthquake. The slope on the right bank of the Sele River is characterised by a large number of springs located at the limit between the carbonate aquifer and the flysch soils. In contrast, groundwater underlying Mounts Ogna-Marzano flows either towards the springs in the vicinity of the Sele River or southwards into another valley.

LANDSLIDE FEATURES AND SPACE-TIME DISTRIBUTION

The areas where carbonate rocks outcrop are only marginally influenced by mass movements: they mostly include rockfalls and topples confined to the steep slopes (mean slope >30°) bordering the carbonate massif. These landslides are less important and are not discussed here. The flysch areas are characterised by low-medium acclivity slopes (10-12°) and widespread creep and landslide phenomena (Agnesi *et al.*, 1983; Budetta 1983; Parise *et al.*, 1996). Complex landslides are widespread, starting as rotational or translational slides in the upper portions and evolving to flow in the medium to lower sectors.

Agnesi *et al.* (1983) have gathered data on 41 landslides occurred before the 1980 earthquake and 50 occurring since: these consisted largely of translational slides and mudslides. Before the earthquake, left-bank and south-westward landslides were moderately prevailing whereas after the earthquake, right-bank and south-eastward landslides (both in the flysch and in limestones and dolomites) were markedly predominant (Figure 1). Moreover, the authors showed that landslides before and after the November 1980 earthquake do not vary significantly in their type and morphology: most landslides were actually reactivated. Statistically, the mean slope of the landslide bodies was modified (from 11.8° to 12.8°), the average length increased slightly (from 879 to 987 m) and the width decreased (from 359 to 333 m).

If (to a first approximation) similar soils are assumed to outcrop in both slopes and cohesion is expected to be modest — as is the case in reactivated landslides — the following thesis may be advanced. The stability of the investigated landslide bodies, which generally progress longitudinally and appear to be particularly 'long' and 'oriented' as a result of the earthquake, is most likely to depend upon the angle of friction and the slope. Given the average increase in slope of the landslide bodies, it might be argued that, on average, the left-bank landslides, which were not reactivated by the earthquake, were much more stable than the right-bank reactivated ones. Further geological and geotechnical investigations are required to elucidate the process.

HYDROLOGICAL INVESTIGATION

The upper valley of the Sele River was investigated thoroughly in view of its hydrological characterisation. The large area of the Apennines under study is separated from the Ionic coast by the Alburni Mountains (1742 m asl) and from the Tyrrhenian Sea by Mount

Table 1 Climatic stations, mean yearly rainfall (MYR, mm) and mean monthly rainfall (% MYR). Type of sensor: P= rainfall, T=temperature, E= evaporation.

Gauge	Name	Type	Height *m asl*	Years	Jan %	Feb %	Mar %	Apr %	May %	Jun %	Jul %	Aug %	Sep %	Oct %	Nov %	Dec %	MYR *mm*
A	ACERNO	PTE	650	1	11.5	11.0	8.9	8.7	5.5	4.9	3.0	3.7	5.7	9.2	13.4	14.6	1699
B	SERRAPULLO	PTE	996	1	10.7	11.1	9.6	7.6	5.0	3.0	1.2	3.0	6.6	11.0	15.6	15.8	1028
C	CASSANO IRPINO	PTE	584	1	10.5	11.4	9.2	8.0	5.2	3.1	1.7	2.7	6.5	11.3	14.7	15.6	1254
D	LACENO	PTE	1120	1	10.3	10.7	9.3	7.7	5.5	4.7	2.7	4.0	7.4	10.4	13.5	13.8	2001
E	LACENO	P	1170	8	11.1	10.6	8.9	7.8	5.7	4.6	2.9	3.3	6.0	9.4	15.5	14.2	1754
F	QUAGLIETTA	P	270	10	11.0	11.1	8.5	7.3	5.8	3.9	2.2	3.0	6.5	11.0	14.7	15.1	1334
G	VALVA	P	612	12	11.9	10.6	8.3	8.0	6.5	4.1	2.1	3.6	6.3	11.8	13.2	13.7	1497
H	OLIVETO CITRA	P	310	6	8.1	10.2	9.0	7.6	6.5	5.4	5.7	4.7	7.7	9.7	9.9	15.7	1322
I	CASTELGRANDE	P	873	12	10.9	13.6	10.4	8.0	6.9	5.3	1.8	2.9	6.2	9.5	11.1	13.4	1347
1	CASSANO IRPINO	P	470	65	10.6	11.4	8.7	8.0	5.5	3.6	2.1	2.9	6.5	11.0	14.5	15.2	1319
2	NUSCO	PT	912	67	10.9	11.3	8.7	8.3	6.0	4.3	2.6	3.1	7.0	11.1	13.0	13.7	1119
3	S.ANG. D.LOMBARDI	PT	870	65	10.5	10.1	8.4	7.7	6.5	5.2	3.1	4.4	7.3	10.4	13.6	12.8	917
4	ANDRETTA	PT	850	67	9.1	9.5	8.3	8.2	6.7	5.5	4.2	4.5	7.9	11.2	12.7	12.2	809
5	CALITRI	P	525	66	9.6	9.5	9.2	8.3	7.2	5.3	4.6	4.6	7.7	10.2	12.1	11.7	755
6	LIONI	PT	540	65	10.6	10.5	8.1	7.4	6.1	4.9	3.0	4.4	7.2	10.5	14.0	13.3	972
7	TEORA	P	660	67	11.4	10.1	8.8	8.0	6.0	5.1	2.9	3.4	6.5	10.4	14.0	13.4	1043
8	S.ANDREA DI CONZA	PT	694	17	11.0	10.0	8.4	6.9	6.0	5.6	3.1	2.7	7.7	11.2	15.1	12.4	950
9	PESCOPAGANO	PT	954	67	10.5	10.5	8.6	7.8	5.9	4.8	3.2	3.4	7.2	10.8	13.5	13.7	1055
10	CAPOSELE	PTE	420	69	11.6	10.9	8.8	8.6	5.9	4.1	2.2	3.5	6.0	10.7	13.7	13.8	1246
11	MATERDOMINI	PT	570	59	12.0	10.3	8.4	7.6	6.7	4.4	2.4	3.7	6.5	11.4	13.5	13.2	990
12	ACERNO	P	720	67	11.4	10.9	8.9	9.1	6.3	3.8	1.8	2.8	6.2	10.6	14.4	14.0	1763
13	SENERCHIA	P	600	69	11.0	11.2	10.1	8.0	5.2	3.2	1.8	2.7	6.2	10.1	14.4	16.0	1654
14	MURO LUCANO	PT	570	66	11.3	10.8	9.3	8.2	5.9	4.8	2.9	3.3	6.6	10.1	14.2	12.7	966
15	CAMPAGNA	P	350	68	12.4	10.7	9.5	7.0	6.6	3.6	1.8	2.7	6.3	10.2	15.5	13.6	1561
16	CONTURSI	PT	200	43	12.9	10.8	8.4	7.7	6.6	3.5	2.4	1.7	6.0	10.9	14.0	15.3	1351
16b	CONTURSI	PT	97	20	9.9	11.4	11.1	8.8	6.4	3.3	1.9	4.7	6.6	10.4	12.6	12.8	1173
17	EBOLI	PT	146	69	11.5	10.6	9.5	7.7	6.9	3.1	1.6	3.0	7.1	11.7	14.0	13.5	1254
18	BUCCINO	P	659	69	10.2	10.9	9.4	8.3	7.2	4.4	2.9	3.4	6.1	10.7	13.7	12.8	988
19	CASTELLUCCIO C.	P	459	67	11.0	10.1	8.5	8.9	5.4	3.9	2.5	3.2	5.6	11.0	15.7	14.4	1001

Table 2 Mean monthly and annual temperature (°C) from temperature gauges

Gauge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
A	4.6	5.0	7.1	10.1	13.9	17.7	20.3	20.4	17.4	12.8	8.9	5.9	12.0
B	3.3	3.8	6.1	9.4	13.5	17.7	20.6	20.7	17.4	12.3	8.0	4.9	11.5
C	4.3	5.0	7.9	11.3	15.3	19.7	22.5	22.7	19.3	14.0	9.4	6.2	13.1
D	0.4	1.0	3.4	6.6	10.6	14.6	17.3	17.4	14.2	9.4	5.1	1.9	8.5
2	3.1	3.7	6.2	9.7	13.9	18.2	21.2	21.3	17.9	12.7	8.1	4.8	11.7
3	4.2	4.7	6.4	9.6	14.0	17.8	20.6	20.7	17.5	13.0	8.7	5.3	11.9
4	2.6	3.7	6.2	10.0	14.3	18.4	21.3	21.5	17.7	13.0	8.1	4.2	11.8
6	3.5	4.1	6.9	10.3	14.4	18.9	21.8	21.8	18.3	13.0	8.4	5.5	12.2
8	4.3	5.6	7.7	10.6	14.4	19.8	23.1	22.6	18.3	14.3	9.5	4.5	12.9
9	2.5	2.9	5.3	8.5	12.8	16.9	19.6	19.4	16.0	11.3	6.8	4.1	10.5
10	3.3	4.0	6.6	10.1	14.2	18.5	21.3	21.5	18.0	12.9	8.4	5.0	12.0
11	5.0	5.6	8.1	11.2	15.3	19.5	22.4	22.4	19.2	14.7	10.1	6.8	13.4
14	5.7	6.3	8.3	11.5	15.5	19.2	22.0	22.2	19.1	14.5	10.4	7.0	13.5
16	7.3	8.0	10.2	13.3	17.0	21.2	24.0	23.8	20.9	17.1	12.5	9.1	15.4
16b	7.3	8.1	9.9	13.4	16.7	20.3	22.8	22.7	20.4	16.6	12.4	9.2	15.0
17	9.5	9.5	11.1	13.6	18.0	21.4	24.5	24.9	21.8	17.5	13.2	10.3	16.3

An array of factors influences the depth of precipitation. Both winds and mountains affect rainfall distribution. Winds carry the clouds formed over the nearest sea (the Tyrrhenian Sea); the mountains speed up water vapour condensation above the slopes and shelter the interior. The first insight on the influence of height on rainfall distribution stemmed from the calculation of the linear regression between the elevation and the rainfall depth (Figure 3). This plot highlighted two groups of stations: one was more or less homogeneously distributed around the regression straight line, while the second included all the remaining stations, where the rainfall rate seemed not to depend on height. The first group comprised stations 1, 10, 13, 12, 15, 16 17, all in the vicinity of Mount Polveracchio.

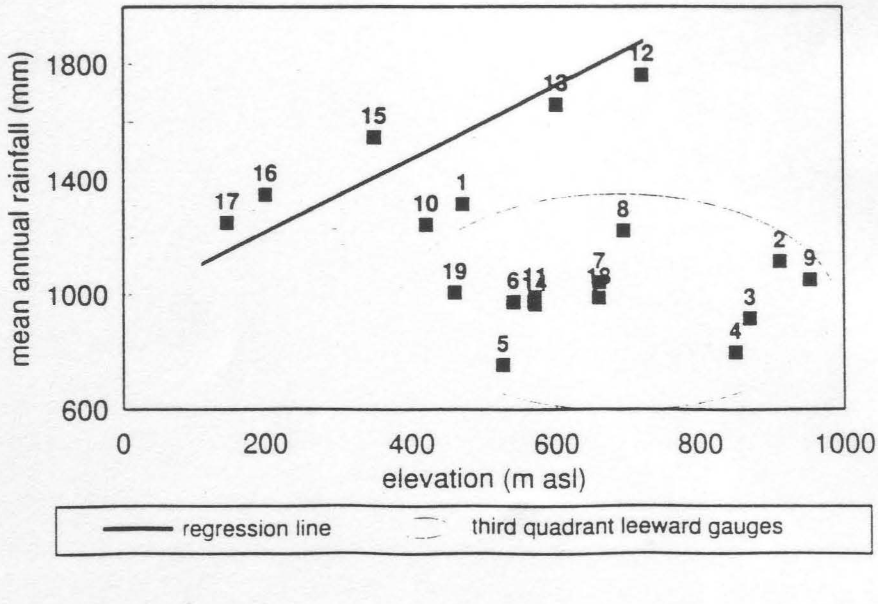

Figure 3 Long duration gauge elevation plotted against rainfall

Here, the influence of the third quadrant winds blowing water-vapour rich air masses from the near Tyrrhenian Sea was strongly felt. When these air masses reach the mountains slopes, they cool and trigger heavy rainfall, which is therefore significantly related to height.

The chart shows that the first group of stations facing east or south-east (10, 13, 15, 16 and 17) lie above and below the regression straight line, whereas the two stations facing west (1 and 12) are below that line. Their behaviour is very similar to that of stations 10 and 13, facing east and at approximately the same distance from the Tyrrhenian Sea. These remarks testify to the limited influence of the slope exposure on rainfall. This parameter may therefore be ignored. Short data series (less than 20 years) are used to increase the spatial density of the stations to gain better knowledge of the spatial variability in rainfall and temperature in the area. A multiple regression method, applied to monthly data, was tried out for this purpose (Polemio and Dragone, 1996) and enabled the calculation of the concomitant relationships between a short data series and a group of long data series, collected by one of two groups of proven homogeneous stations.

Each short duration station was then associated with one of the two sets of long duration stations, according to the location and statistical findings. Monthly data pertaining to the available common measuring years were selected and a multiple linear regression analysis was conducted. The regression was applied to each station (A to I), using a maximum of eight independent stations, according to the circumstances (Polemio and Dragone 1996). The optimum correlation coefficient was never below 0.98. Once the multiple regression coefficients were known, the mean rainfall of short duration stations was inferred from that of long duration stations (Table 1). Values plotted without taking altimetry into account (Figure 3) confirmed the assumptions.

A basically linear relationship has been found between the average annual air-temperatures and the elevation: the lower the topographic elevation, the lower the temperature, for all gauges (Table 2). Therefore, it can be generally stated that this parameter does not depend on the distance from the sea, and furthermore it is only moderately influenced by exposure.

A mean value of monthly and yearly temperatures for short duration stations was also inferred. Data were similarly satisfactory but are not reported here for the sake of brevity. Based on the results of this research and consistent with bibliographic data, the thermal variables showed no significant impact on the investigated instability phenomena. A brief treatment of rainfall follows.

RAINFALL AND LANDSLIDE PRONENESS

From the altimetry standpoint, the raingauges did not ensure good coverage (Table 1). This is why the impact of the direction of humid winds and altimetry on rainfall distribution was investigated using the co-kriging method. Data used to map rainfall through the co-kriging method (Figure 4) are reported in Table 1. The estimated height was inferred from the nodes of a square-mesh grid. Each side of the grid was 850 m long, the squares were 50×50 m. Topographic data were derived from 1:50 000-scale maps.

Analysis was carried out to establish the height and the mean annual rainfall on a regional basis and thus to limit the drawbacks of missing raingauges at the peak elevation. The preliminary statistical analysis suggested that the variables under investigation were substantially anisotropic. Therefore, the structural analysis was carried out on directional

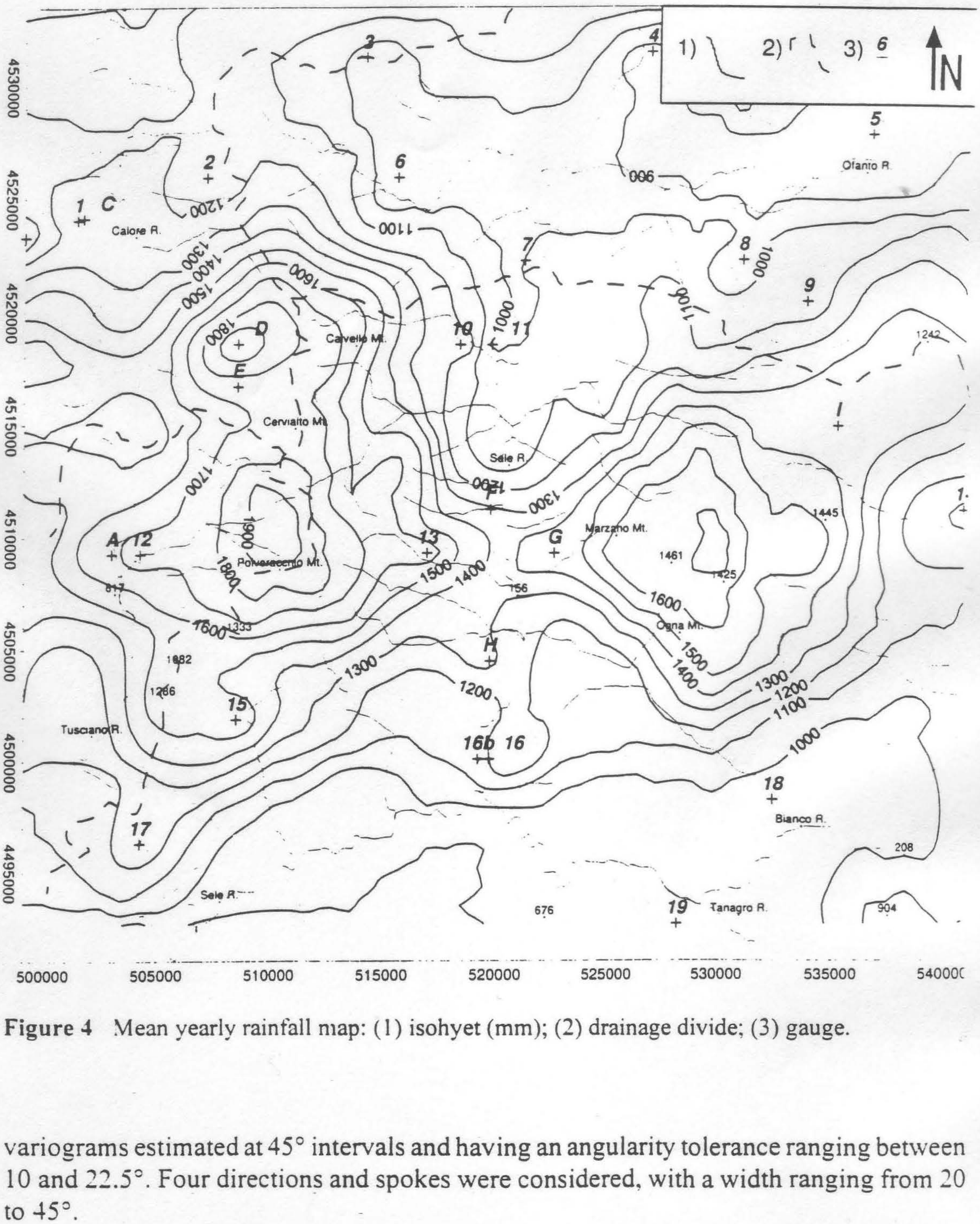

Figure 4 Mean yearly rainfall map: (1) isohyet (mm); (2) drainage divide; (3) gauge.

variograms estimated at 45° intervals and having an angularity tolerance ranging between 10 and 22.5°. Four directions and spokes were considered, with a width ranging from 20 to 45°.

The mean rainfall axis was oriented N71°E. This finding is consistent with the hydrological-statistical study. The direction is found in the ellipsis of the variograms, as a result of the humid winds that push air masses from the Tyrrhenian Sea and are responsible for the rainfall in the area. The variogram was modelled using an exponential function with no 'nugget' effect: the ellipsis anisotropy was 0.71. The main orientation of the height was N173°E: in practice the direction was N-S. This finding complies with the morphology of the area which is conditioned by the orientation of the valleys of the Rivers Sele, Tusciano and Calore. The variogram was modelled using an exponential function with a 'nugget' effect: the ellipsis anisotropy was 0.43. The co-analysis of the two variables was conducted assuming an isotropic cross variogram described by a spherical model. More complicated and time-consuming trials proved unsatisfactory. Most of the drawbacks found were due to a poor correlation with the main variable — the mean annual rainfall — which was sampled to a lesser extent than the secondary variable. This might lead to underestimating the secondary variable and hiding some of the data highlighted by the co-kriging method. Based on the findings of the structural analysis of the 'region-based' variables, the co-kriging was then calculated using the same grid from which height data had been derived.

Three different approaches were applied (Deutsch and Journel, 1992): the Simple Cokriging (SC), the Traditional Ordinary Cokriging (TOC) and the Standardised Ordinary Cokriging (SOC). The best results were yielded by the SOC method which tends to overestimate the secondary variable, thus creating a fictitious secondary variable, the mean of which is equal to that of the main variable. Note that the final results differ from those obtained by using the kriging. The effect of the relief on the one hand and the role of the anisotropy of both variables on the other hand originated a concentric trend around the main reliefs. This effect, which is both justified and positive while determining the space variability of mean annual rainfalls, is equally strong on Mount Marzano and, in general, on the left side of the Sele Valley, making up for the absence of stations on that side.

The maximum measured mean annual rainfall coincides with the maximum calculated value. This undoubtedly implies an underestimation of the maximum rainfall values which should occur close to the peaks of Mounts Polveracchio and Cervialto. However, the relief-effect is largely described and it confirms the significant difference in rainfalls between the two sides of the Sele Valley. Note that the mean annual rainfall is decidedly higher on the right side of the Sele Valley. Nevertheless, the historical proneness to landslides, witnessed by those that have occurred since 1980, seems to suggest that the left side was affected by a higher number of landslides. Therefore, it may be assumed that rainfall is only moderately liable to trigger landslides in this morphological framework. This consideration is in line with the findings Polemio (1997) derived from a detailed study of four landslides in Senerchia, one of which followed the 1980 earthquake, and using a statistical-hydrological approach applied to the study of up to 180 days of daily cumulated rainfalls.

Once data on rainfall distribution and conditioning parameters were known, rainfalls in 1979-80 were selected. At each available station, rainfalls during a month were calculated backward up to a total of 12 months. To simplify, the rainfalls of November were taken into account, even though the earthquake had occurred on the 23rd. The approximation is not a crude one, since in the remaining days of November, only three or four days were rainy and many landslides were activated some days after the earthquake.

In order to detect precisely the amount of rain fallen before the 1980 earthquake and landslides, rainfall depths were expressed in terms of percentage of the corresponding historical mean values. For the shortest period of time (one month) the maximum value was 237% (station 12); the minimum value was 110% (station 6) and the mean was 162%. Hence, rainfalls in November 1980 were generally heavy and sometimes heavier than the average. By increasing the duration, the statistical values were progressively decreased. The values over 12 months were the following: minimum 72% (station 13), maximum 138% (station 12) and mean 106%.

The spatial distribution of values was similar. The two cases described (Figures 5 and 6) show that during the twelve months before the 1980 earthquake heavy rain fell on all the carbonate relief west of the investigated area, especially along and around the watersheds between the Rivers Sele-Tusciano, Sele-Calore and Ofanto-Calore. Therefore,

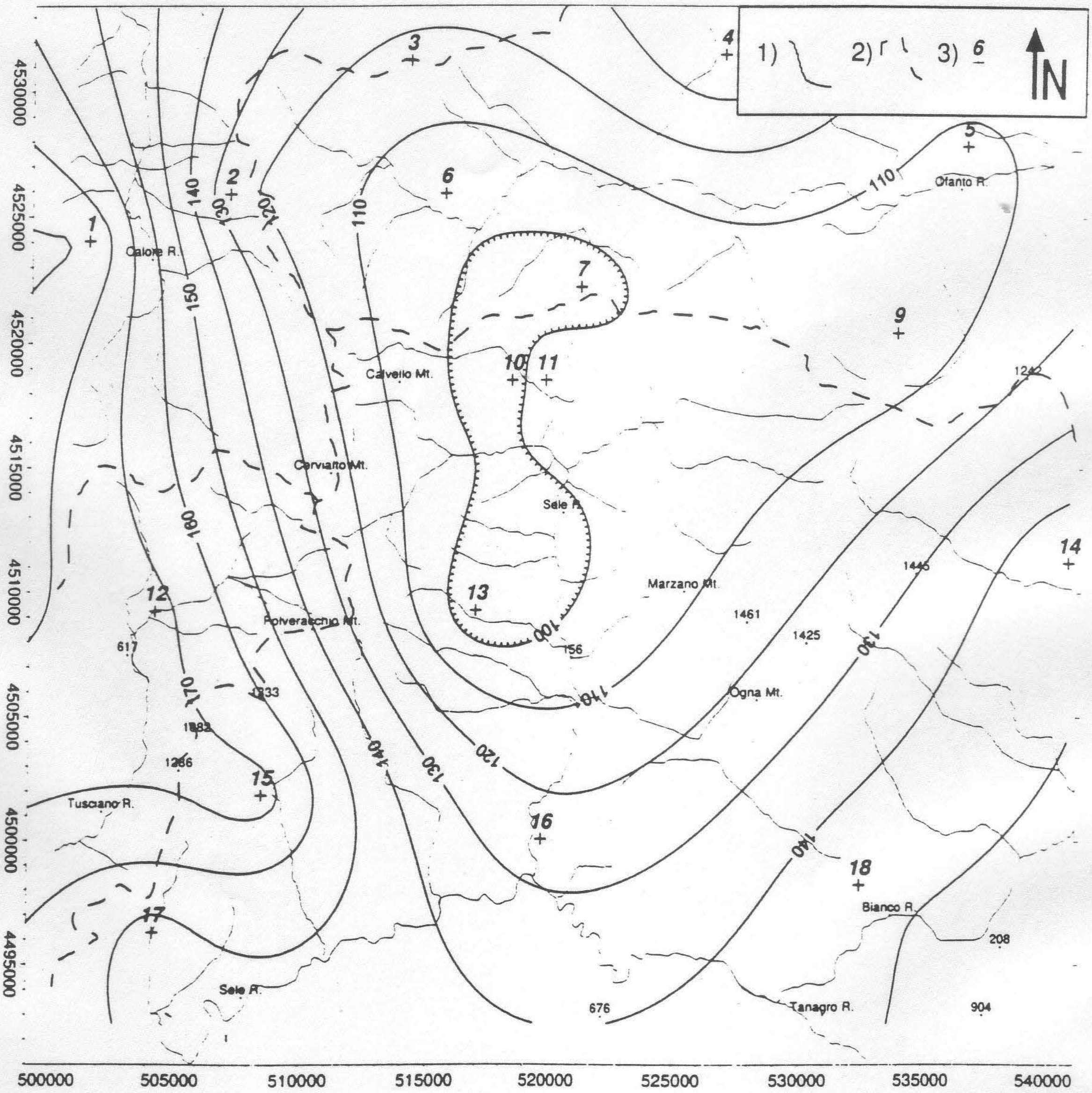

Figure 5 Total rainfall over the three months before the 1980 earthquake, expressed as a percentage of the historical mean: (1) isohyet (%); (2) drainage divide; (3) gauge.

runoff and infiltration were increased in the large and deep aquifers that make up these mountains as well as in the corresponding hydrological systems.

Average rainfall was recorded on the eastern or left side of the valley. The minimum values of relative rainfall events were always recorded, as the duration varied, along the medium-lower portion of the slope, where landslide-prone flysch soils are found. The charts show a distribution of minimum values on the right side. Despite the statistical efforts, the result is biased by the number of stations available in 1980. However, the final picture is quite clear. The rainfalls on the landslide bodies activated by the 1980 earthquake and in the surroundings cannot account for the distribution of these landslides, agreeing with the results obtained by others (Cotecchia and Nuzzo, 1986), who applied different approaches and scale. By contrast, calculations suggest that both the non-ordinary runoff within the hydrographic system and the non-ordinary recharge of the carbonate aquifers may have had an impact on landslide distribution. This might account.

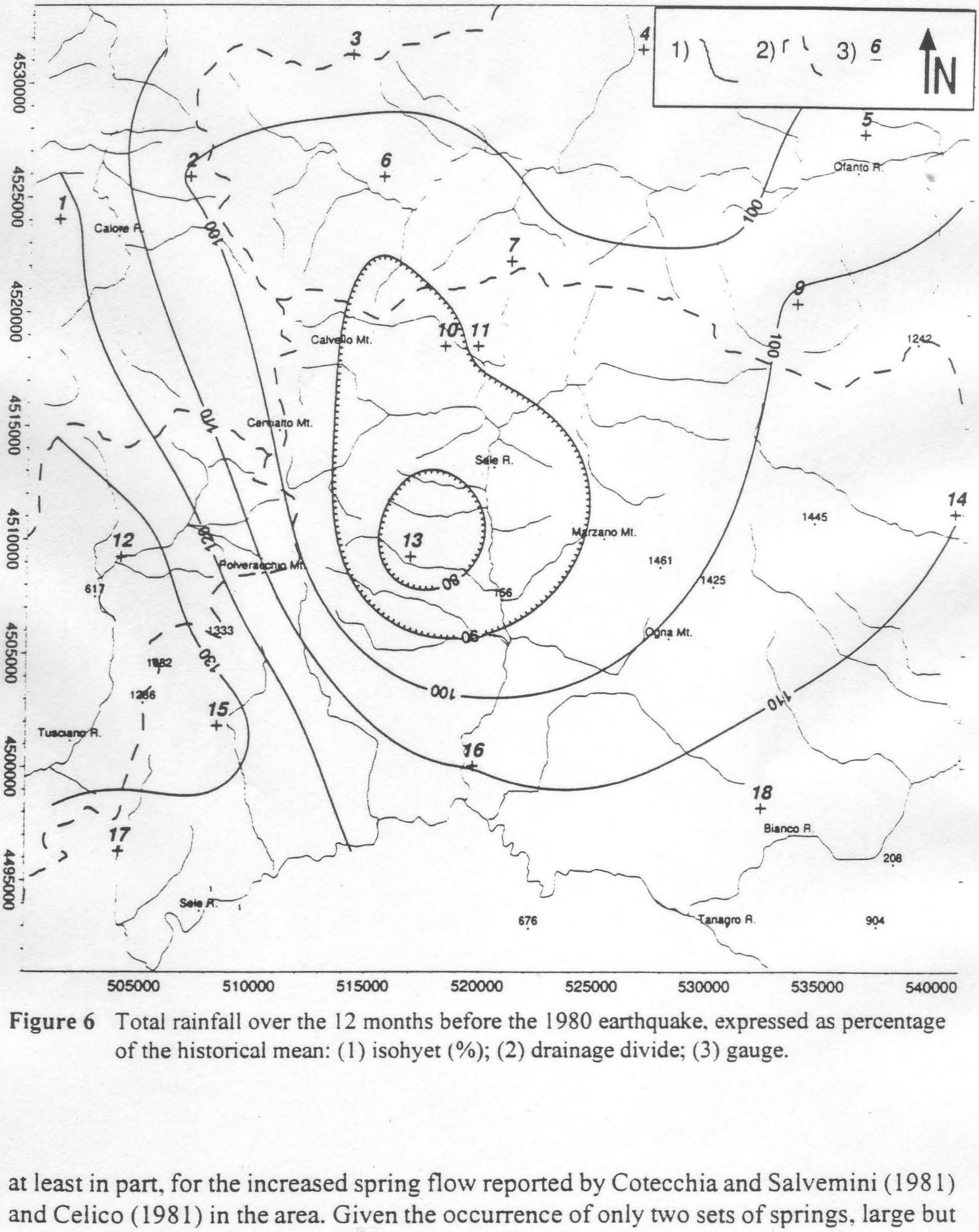

Figure 6 Total rainfall over the 12 months before the 1980 earthquake, expressed as percentage of the historical mean: (1) isohyet (%); (2) drainage divide; (3) gauge.

at least in part, for the increased spring flow reported by Cotecchia and Salvemini (1981) and Celico (1981) in the area. Given the occurrence of only two sets of springs, large but non-barycentric, Cotecchia and Salvemini assign the flow-rate increase to earthquake-dependent topographic changes. Celico, although stressing the important contribution of the earthquake, attributes the spring flow-rate increase to a rise in the piezometric surface due to pressure variations in the voids and detects the effects of previous rainfalls in one of the two sets of springs.

However, in previous studies only some rain stations were taken into account, such as that of Caposele (No. 10) where rainfall was particularly low in 1980. Other stations were ignored, such as Acerno (No. 12), which had an impact on the carbonate aquifers and where rainfall was much heavier in 1980. The impact of groundwater circulation on the

Sele Valley landslides is far from being thoroughly explained. Further detailed studies are required on discharge hydrographs and flow patterns along the slope as a whole.

CONCLUSIONS

This study provides a general framework for investigating the impact of temperature and rain on landslide distribution in the upper valley of the Sele River. It has shown that the distribution of these variables, particularly mean annual rainfall, does not account for the different behaviour of the two valley sides as a result of slope dynamics.

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