Understanding rainfall-landslide relationships in man-modified environments: a case-history from Caramanico Terme, Italy

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Abstract The expansion of Caramanico Terme in this century has led to the urbanization of marginally stable valley slopes, and this has coincided with the apparent acceleration of landslide processes. Recent landslides on man-modified slopes were caused, but not necessarily triggered, by heavy precipitation (antecedent moisture was a more critical factor than the amount of storm rainfall). Because no important landslides on natural slopes in the same period were reported in the Caramanico area, a clear distinction must be made between natural settings and those modified by man when determining rainfall thresholds for predictive purposes. In recently urbanized mountainous environments, the thresholds used to assess landslide hazards should not be weighted too heavily on old historical records of precipitation and associated mass movements. Instead, more weight ought to be given to the period following the occurrence of any major anthropogenic and natural (e.g. high-magnitude earthquake) modification of slope setting.

Key words Rainfall · Landslide · Man-modified slope · Italy

Introduction

Landslides are complex phenomena, whose time-space distribution results from an interaction of numerous factors: geological, geomorphological, physical, human (e.g., Varnes 1978; Crozier 1986; Cruden and Varnes 1996). It is generally recognized that most of them evolve more or less slowly to what might be termed a catastrophic stage, characterized by a sudden increase in deformation rate and the occurrence of major displacements. Furthermore, the length of the preparatory stage may vary from weeks to many years. Unfortunately, as a great majority of landslide studies typically begin post factum, often very little is known about the relative importance of different causative processes and the exact sequence of events which lead to the initiation of the main failure.

Despite the difficulties in reconstructing the pre-failure history of landslides, there is no doubt that rainfall events represent the most common causative factor. The existence of correlations between meteoric events and mass-movement initiation is based on observational evidence and is supported by numerous studies (Govi and others 1985; Canuti and others 1985; Wieczorek 1996; and references therein). Furthermore, it has been shown that models of rainfall thresholds might be developed to give time-specific warnings for slope failures (e.g., Keefer and others 1987). The predictive resolution of these models is that of a regional scale and their applicability might be limited to rather shallow mass movements (Church and Miles 1987; Walker and others 1987; Johnson and Sitar 1990).

It appears, however, that among numerous possible causes and triggers of slope instability, the relative importance of precipitation on landsliding is sometimes overemphasized, and its role oversimplified. For example, several processes which can significantly modify water input are often not accounted for, such as convergence of surface runoff and groundwater flow, snowmelt or rain on snow episodes, evapotranspiration, as well as effects of accelerated erosion during severe storms. The reason for emphasis on rainfall over other controlling variables is that rain is easily detected and often continuously monitored such that the relevant data are readily available for statistical analysis. Moreover, meteoric processes can be conveniently treated as cyclic events (e.g., rainy seasons alternating with dry periods).

Nevertheless, slopes need to be considered as continuously changing complex systems (e.g., Carson and Kirkby 1972). Their evolution to stable or unstable forms is typically controlled by numerous geomorphological, physical, and, to an increasingly greater degree in recent times, man-made processes (cf. Crozier 1986). Because the rates of these processes may be extremely variable, the changes they generate in the slope system can hardly be considered cyclic and easy to predict. Therefore, even if apparently similar episodes of mass movements occur on the same slope, the number of destabilizing factors, their re-

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lative weight and the sequential relation cannot be assumed to be constant. Every landslide therefore is the result of a unique combination of different processes, which is the underlying reason for why the time-space predictions of mass movements will remain difficult. Thus forecasts based on a single cause (e.g., intensive rainfall) might be valid only if it is demonstrated that other factors are not significant.

This study draws on several examples of recent slope failures from the municipal territory of Caramanico Terme (south-central Apennines) in order to illustrate some problems which complicate relations existing between rainfall events and landslide occurrence. The examples include mainly the events which occurred and were examined during the last 7 years of frequent field controls. The selected cases represent partial remobilizations of older slide bodies and enlargements of long-lived slope movements. Therefore, in addition to the definition of their geologic and geomorphic characteristics, particular attention was paid to the reconstruction of the pre-failure activity (state, distribution, and style, cf. WP/WLI 1993) of the phenomena and the most recent slope history, including any changes introduced by man. The field data were integrated with the information obtained from a comparison of a time-series of air photos and a review of historical records.

The recent mass movements were either associated with heavy rainstorms (3-day average duration), or with prolonged periods of precipitations; they all occurred on man-modified slopes. Taking into account that in the same period no large or destructive landslides on natural slopes of similar geological settings were reported in the Caramanico area, special attention is drawn to the increasingly greater human impact on the environment in the last few decades, and to what it implies for the time-space distribution of slope failures at present and in the future.

Physical setting and local geology

Caramanico Terme is a small but important thermal center and holiday resort located in the south-central Apennine mountains, about 50 km inland from the Adriatic sea coast. The medieval part of the town rises from elevations of 450 m, just south of the confluence of the Orfento and Orta rivers, and extends to 650 m a.s.l. along the carbonate ridge which separates the two river valleys (Figs. 1 and 2).

The municipal territory of Caramanico Terme is situated in the intermontane valley known in geological literature as the Caramanico-Campo di Giove depression (Catenacci 1974). The Quaternary neotectonic activity resulted in a significant uplift of the region (Demangeot 1965; Ambrosetti and others 1982). The high seismicity of the area (Postpischl 1985) suggests that neotectonic movements are still occurring. Thus the persistence of high local relief and strong river downcutting are the main geomorphic factors responsible for the recurrent landsliding.

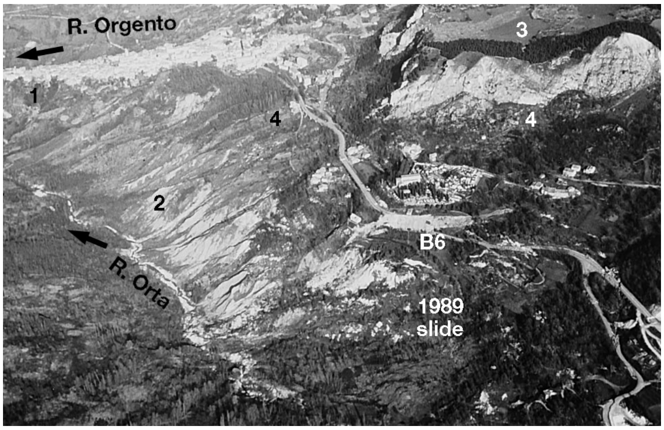

Fig. 1
Helicopter view of the Caramanico area; the viewing direction is to the north. The old town is situated in the upper left of the photo. Note also the cemetery (just right of center), and the 1989 Caramanico landslide area (lower right), whose mainscarp closely follows route SS 487, and the site of borehole B6 marked by an *asterisk*. The group of houses in the center belongs to Case Mancini locality. Numbers correspond to the four main groups of rocks discussed in the text: 1 = fault-bounded carbonate ridge composed of limestones; 2 = Pliocene mudstones; 3 = carbonate megabreccia caprock; 4 = thick superficial deposits covering large slope areas

The geo-structural setting of the Caramanico area and lithostratigraphic relations between the various units have been discussed by Wasowski and Fiorillo (1991) in reference to slope instability. A brief outline of some local geologic features pertaining to the mass movement evolution is given.

The rocks which crop out in the study area can be divided in four main groups (Fig. 1): (1) fault-bounded carbonate structure composed of highly tectonized limestones (Cretaceous?) where the oldest part of Caramanico is situated, and calcareous rocks (Paleocene Miocene) of the Orfento river gorge; (2) marly mudstones including sandstone intercalations up to 3 m thick (Early Pliocene; Buccolini and others 1992) of the Orta valley, (3) an areally extensive ($\sim 2.5\ \mathrm{km}^2$) deposit of carbonate megabreccias several tens of meter thick (Villafranchian; Demangeot 1965), which forms the caprock of the Caramanico hillslopes, and (4) variably thick (from few to tens of meters) surficial materials (Quaternary) of inferred “dry” alluvial fan origin (Wasowski 1996a); they include debris flow deposits (carbonate clasts extremely variable in size with or without clayey-silty-sandy “matrix”), water-laid and eluvial sediments (Fig. 3); these materials mantle large portions of hillslope areas.

Some urbanized areas contain also layers of artificial ground up to 6.5 m thick (fill and domestic rubbish materials).

The chronic instability of the Caramanico hillslopes is strongly linked to the particular hydrological setting determined by the presence of thick megabreccia caprock

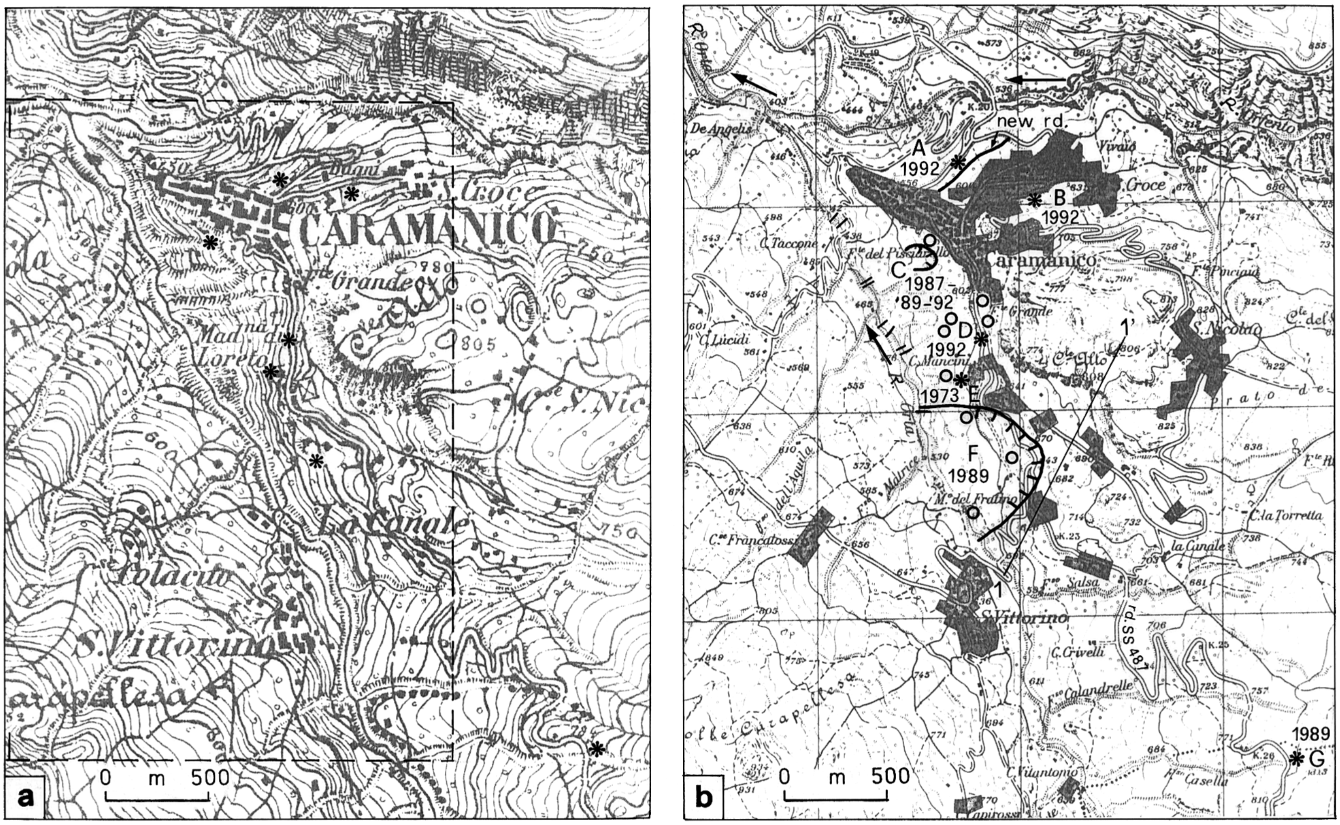

Fig. 2a,b
Comparison of two topographic maps illustrating urban expansion of Caramanico Terme in this century and related changes in surrounding environment. **a** Situation at the begining of the century as shown on the 1907 map; to facilitate a comparison with landslide distribution on part b, the same locations of recent mass movements are indicated with *asterisks*; the *dashed line rectangle*, defined so as to include two areally equal zones on the SW and NE valley sides of the Orta river, represents the sample area used for semiquantitative estimates of the human-induced changes in the Caramanico territory; although not marked on part b, the equivalent area on the 1986 map was considered for comparison. **b** Current situation with 1986 data on urban development (the topographic base map is from 1955); *dark areas* indicate densely populated zones; locations of landslides (marked by *asterisks* with associated capital letters A–G), and their dates (year) refer to following events discussed in the text: A = municipal swimming pool rotational slide, B = Cappuccini Monastery rotational slide, C = long-lived Pisciarello slump-earthflow (with mainscarp shown), D = 1992 route SS 487 failure, E = Case Mancini failure, F = 1989 Caramanico landslide (with mainscarp and lateral limits shown), G = 1989 route SS 487 earthflow; *small open circles* mark locations of springs and *black arrows* indicate flow directions of Orta and Orfento rivers; note also positions of checkdams on the Orta river reach extending from the old town to northen flank of 1989 Caramanico landslide (dams are marked with *short black lines*); line 1–1' marks the location of the geological profile shown in Fig. 7

and middle-upper slope apron made predominantly of carbonate debris, and the relatively impermeable clay-rich substratum (Fig. 3). Some of the long-lived and currently active mass movements on the Orta valley slopes are intimately associated with the springs which drain the surficial cover aquifer (Fig. 2b; Wasowski 1996a). Basal slip surfaces of slope failures have developed preferentially along the top of the mudstone substratum or within its uppermost and most weathered part (Lollino and Wasowski 1994). Furthermore, the surficial covers on the slopes facing the Orfento river contain large volumes of loose carbonate breccias and highly fractured evaporitic rocks such as gypsum, set in silty sandy "matrix". Their susceptibility to dissolution and internal erosion (piping) can locally have negative effects on slope stability.

A detailed discussion on the hydrogeology of the Carmanico area is not feasible due to lack of adequate quantitative data; therefore, only a brief description is offered here. Based on the differences in relative hydraulic conductivity, three hydrogeologic units can be distinguished in the area studied.

The first is the *low-conductivity mudstone substratum* – significant local variations in conductivity can occur due to the presence of intensely fractured horizons and thick (typically from one to several meters) shear zones (Wasowski and Fiorillo 1991). Several of these variably sealed shear zones were intercepted by boreholes at depths ranging from 30 to 122 m, within a much less disturbed mudstone sequence (Fig. 4); based on their apparent listric geometry, these features can be associated with low

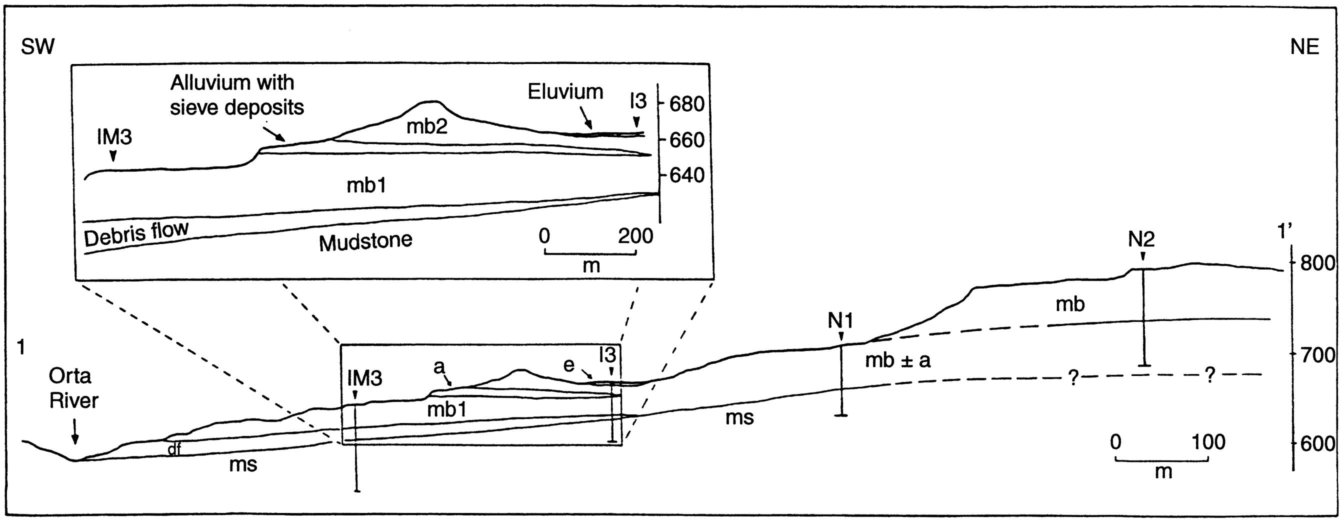

Fig. 3
Geological profile of the versant partially affected by the 1989 Caramanico landslide (see Fig. 2b for location). Symbols: ms = mudstone substratum; df = clay-rich deposits with sparse carbonate clasts, of inferred debris-flow origin; mb1 and mb2 = respectively, lower and upper units of very coarse carbonate debris ("megabreccia"); a = alluvium including sieve-like carbonate deposits; mb ± a = undifferentiated carbonate "megabreccia" and alluvial deposits; mb = carbonate megabreccia caprock; e = eluvium; IM3, I3, N1 and N2 = borehole names

angle faults or deformation levels generated by deep-seated gravitational slope movements. Some of these zones can locally perch ground water. In addition, confined groundwater may be present inside the rare medium-grained sandstone beds up to 3 m thick.

Although the overall structure of the unit (a dip-slope stratification with bed inclination few degree lower with respect to the average slope of the topographic surface) would point to the existence of a rather simple subsurface flow pattern, the groundwater circulation is complex due to the presence of the major fracture discontinuities and local folding observed in the lower part of the versant. This interpretation is confirmed by the results of post-mortem piezometric monitoring of the 1989 landslide (Buccolini and others 1995). In particular, the three electric piezometer cells positioned in sheared and fractured zones of the mudstone substratum revealed significant variations of piezometric pressure (from less than 100 to over 400 kPa). The oscillations of up to 110 kPa were registered in the cell located near the top of the unit.

The second distinguishable hydrogeologic unit is *high-conductivity megabreccia caprock*. Due to high porosity (enhanced also by solution and fractures caused by faulting), considerable areal extent and thickness, and the presence of the underlying mudstone substratum (aquiclude), this unit represents the main groundwater aquifer in the area. The outcrop relationships indicate that the megabreccia reservoir receives only rainfall water. This mechanism of recharge results adequate considering the relatively high average annual precipitation in the area (Fig. 3), and the absence of surface runoff. The simple water balance estimates, suggest that the average discharge of the megabreccia unit amounts to 50–80 l/s (Lanzavecchia 1973). The lack of springs at the base of the megabreccia caprock, and the presence of several contact springs of medium discharge (< 5 l/s) in the middle-lower part of the versant facing the Orta river (Fig. 2b), imply that an important quantity of the groundwater is transmitted downslope through the unconsolidated surficial deposits.

The third unit comprises *medium-to-low-conductivity surficial covers*: due to the significant thickness (Fig. 3), predominance of carbonate breccia materials over clay-rich sediments, and the presence of the underlying mudstone substratum, this unit is capable of hosting a shallow aquifer. The observed rapid lateral and vertical changes of lithofacies of these unconsolidated deposits (consistent with their origin in an old alluvial fan, and in part enhanced by the post-sedimentary disruption related to the long history of landsliding), the presence of extremely permeable and practically impermeable sediments (sieve and mud-rich deposits, respectively), with the particle size variations from clays to house-size carbonate breccia blocks, and the irregular topography of the substratum (with local lows and highs), imply that the groundwater flow pattern is very complex. This assumption is confirmed by the highly variable water level rises (from less than a meter to 11 m), registered in the Casagrande and open-pipe piezometers situated within the surficial cover materials, within the limits of the 1989 landslide (Buccolini and others 1995). Furthermore, water levels coincident with the ground surface were observed in two wells during winter 1990/1991. For most of the year-long monitoring, the surficial covers resulted to be partially saturated. The existence of high hydraulic conductivity contrasts within the complexly layered colluvial sequences can often result in perched water tables or confined water con-

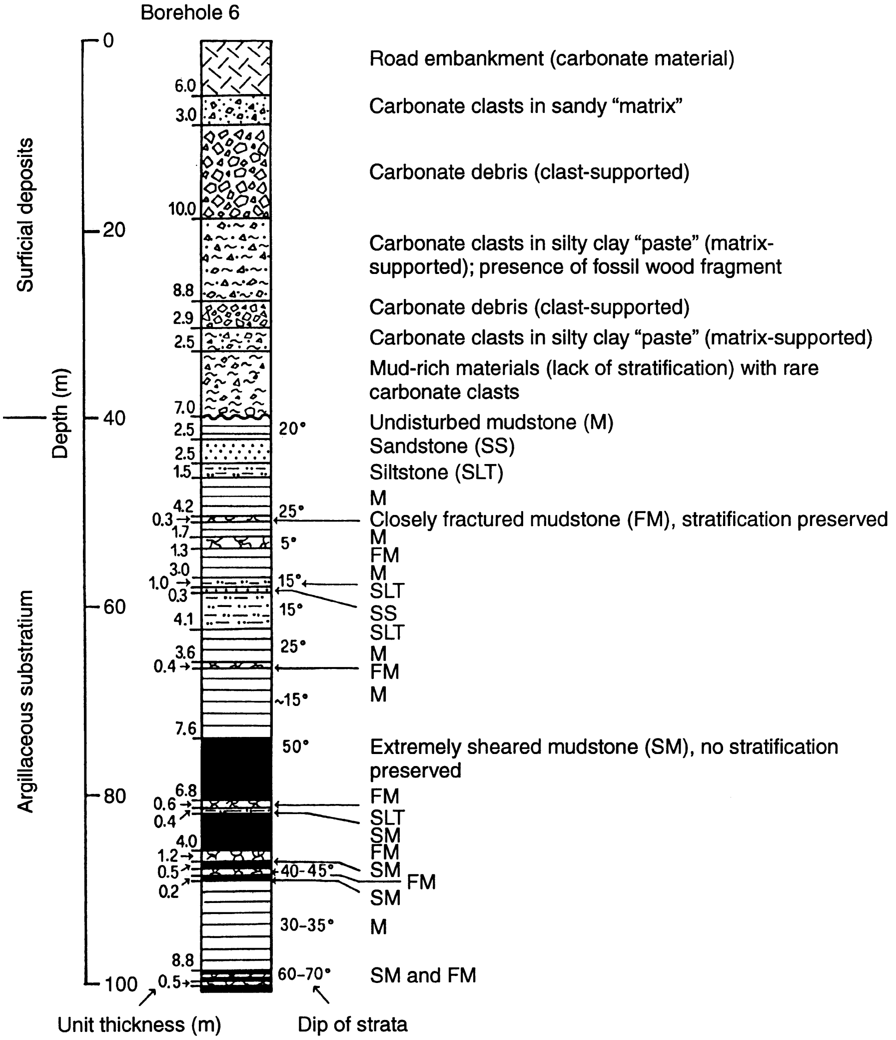

Fig. 4
Detailed litho-stratigraphic log of borehole B6 drilled in the head zone of the 1989 Caramanico landslide (see Fig. 1 for location); note multilayer stratigraphy of the surficial deposits and the presence of several thick shear zones within the mudstone substratum

ditions, and this typically leads to instability (Hodge and Freeze 1977). The stability of the slopes in Carmanico is further aggravated by the unusual thickness of the surficial covers and the irregularities of the impermeable substratum, which can concentrate groundwater flow (Wasowski and Fiorillo 1991).

Town development and distribution of landslides

Expansion of Caramanico this century led to the urbanization of marginally stable hillslope areas on the middle-upper valley slopes of the Orfento and Orta rivers. The changes which took place can be appreciated from the comparison of two topographic maps, one from the beginning of the century and the other from 1986 (a and b of Fig. 2a, respectively). The 1907 map shows the town developing principally in a narrow zone which follows the ridge dividing the two rivers. This area is not susceptible to landsliding because the outcropping limestone substratum forms a flat-topped topography of the ridge summits. The 1986 map illustrates that the main town has grown considerably outside its old limits, and that new housing development has taken place in its peripheries. This new urbanization occured mostly in hilly areas subject to mass movements in the past.

In an attempt to quantify the man-made alteration of slopes in the Caramanico area during this century, two areally equal zones (approximately 3.5 km^2 each) were selected on the opposite sides of the Orta river (Fig. 2). The determination of human interference was related to the increase in area (expressed as areal frequency) of the densely populated zones; for simplicity, the latter included only the urbanized sites with two or more housing buildings. The comparison of the two maps revealed that the major changes took place on the NE valley side of the Orta river, where the town of Caramanico is situated. The areal frequency of the densely populated zones increased there from 5.2 percent at the beginning of the century to 13.3 percent in 1986. In the same period the pace of urbanization was much slower on the SW valley side (increase from 2.2 to 3.1 percent).

In general, the density of the road network has not changed considerably since 1907. Instead, most of the

pre-existing routes have been widened, levelled, and straightened, whereas some others have been locally rerouted. In particular, the road connecting Caramanico Terme with towns situated up- and down-valley has been upgraded to a major transportation line SS487; this modification has locally resulted in a major impact on the NE side of the Orta valley, with local increases in slope inclinations from 36–39 to 71–82 percent (Lanzavecchia 1973). The changes of the secondary country roads on the SW, and much less populated valley slopes, have involved mainly adjustments of road-beds to private car traffic.
Figure 2 shows the locations and years of occurrence of better-documented landslide events in this century in the Caramanico territory. Most of them fall in the new growth areas and appear to be linked with the road network. In addition, the great majority of these slope failures has taken place in the last 10 years, which suggests that the failures may have been induced by human activities. New urbanization, which had already begun in the sixties, has continued at an accelerated pace (particularly in the period 1975–1985) until the late eighties. The information received from the Caramanico Technical Office (Mr. V. Silvestri, personal communication 1996) indicates that the rate of development (especially as regards the state funded constructions) has slowed down significantly in the first years of the current decade.

People have also had a positive impact on slope stability. Until the fifties, agriculture was an important part of the Caramanico economy. In order to optimize their crops or to protect the fields or both from erosion, the local farmers took good care of simple surficial drainage works existing on the hillslopes (Lanzavecchia 1973). This helped to reduce the rise of groundwater levels during rainy periods. However, starting from the sixties, Caramanico experienced a continuous growth of thermal industry and tourist-based economy (Senta 1982). The agricultural practices were progressively abandoned, and with that, the maintainance of the drainage works. The resulting higher groundwater levels probably aggravated the mass-movement problem, especially on the WSW facing hillslopes of the Orta river (Fig. 2).

People also had an important impact on the fluvial dynamics of the Orta river, whose lateral erosion has negatively influenced the stability of its valley slopes. For example, in the mid-fifties several check dams were constructed on the approximately 1-km river reach which extends between the old town to the down-valley limit of the 1989 Caramanico landslide (Fig. 2). Although the overall beneficial effects of this intervention on the environment are uncertain, locally it at least reduced the toe erosion of some earthflows (e.g., Pisciarello landslide, Fig. 2), and thereby might have helped decelerate their activity. However, the landslide problem has possibly been transferred up-valley (note the distribution of check dams and the location of the 1989 mass movement in Fig. 2b). At least since late 1989, in part due to the lack of maintenance (last repairs were conducted in 1973), some check dams have been seriously damaged, and their role has been no longer significant.

Rainfall characteristics and landsliding

The rainfall data available for Caramanico span the period 1922–1994. The precipitation records were produced mainly by the Caramanico pluviometric station; for the years 1973–1985, the S. Eufemia station data were used (town located only a few kilometers up-valley and characterized by similar average annual rainfall). The average yearly precipitation of Caramanico is around 1250 mm. The variations of annual rainfall from 1922 to 1994 are shown in Fig. 5. The distribution of precipitations throughout a year is illustrated in Fig. 6. In addition to monthly averages and maxima registered in the 1922–1994 period, the Fig. 6 includes the monthly data for the years 1989 and 1992, characterized by the occurrence of several landslide events. The most rainy months are November and December with about 150 mm average precipitation. However, the record of monthly rainfall total belongs to the month of October (over 600 mm in 1934). Summer seasons are typically very dry and the months of July and August are characterized by the lowest precipitation rate (approx. 50 mm on average).
Most of the recent landslide events in Caramanico were associated with heavy precipitations with duration periods varying from 2 to 5 days. The data pertaining to 12 storms and their antecedent cumulative rainfalls for 15-, 30- and 60-day periods are summarized in Fig. 7. For comparison, the sample includes events which resulted in mass movements, as well as those which apparently did not contribute to slope failure. Aside from the influence of the antecedent precipitation, the compilation suggests that well over 100 mm of rainfall in an event is necessary to produce the most damaging deep landslides (depths about 10 m or more). Storms characterized by lower rainfall totals appear capable of generating only shallow mass

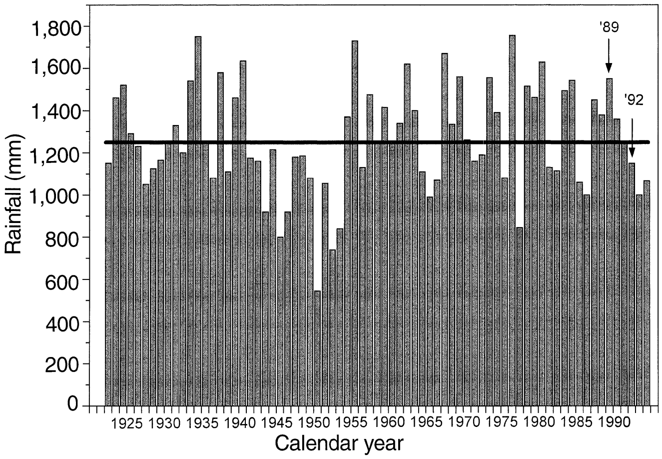

Fig. 5
Yearly rainfall totals in Caramanico from 1922 to 1994. The *heavy black horizontal* line indicates average annual precipitation (1250 mm). *Arrows* point to the amounts of precipitation in 1989 and 1992, two years characterized by several rainfall-related landslide events

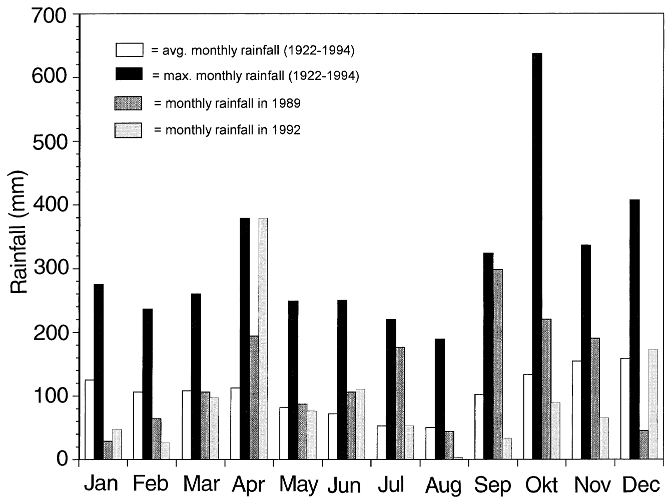

Fig. 6
Average monthly distribution of rainfall and monthly maxima registered in the period 1922–1994 in Caramanico; for comparison, monthly precipitation in 1989 and 1992 are included

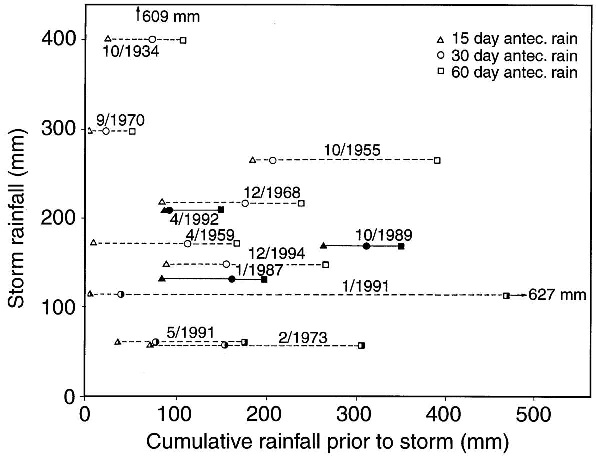

Fig. 7
Storm and antecedent cumulative rainfall for 12 storms in Caramanico. *Filled symbols* indicate meteoric events which resulted in most damaging deep (>10 m) landslides; *half-filled symbols* denote precipitation associated with predominantly shallow mass movements; *empty symbols* refer to six selected heavy rainfall storms which aparently did not cause landslides; for storm durations see Fig. 8

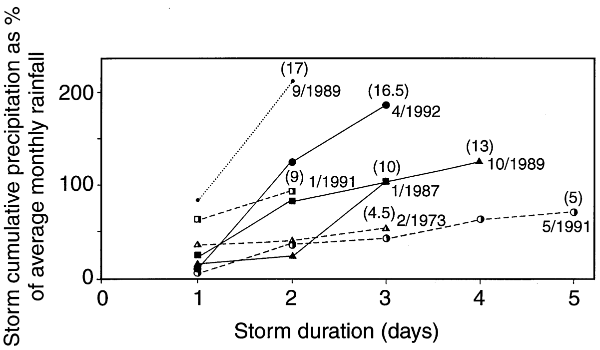

Fig. 8
Storm duration and storm cumulative precipitation expressed as percentage of average monthly rainfall for seven storms in Caramanico; numbers in parenthesis indicate storm rain totals expressed as percent of average annual precipitation; *filled symbols* indicate meteoric events which resulted in most damaging deep (>10 m) landslides; *half-filled symbols* denote precipitation associated with predominantly shallow mass movements; the *dotted line* indicates rain record of the very intense storm of September 1989, which alone did not trigger any mass movement, but represented an important preparatory casual factor for October 1989 landsliding

movements, especially in winter-spring periods which are characterized by higher groundwater levels following the most rainy months, which also include snow precipitation (Fig. 6). This observation is well illustrated by the May 1991 widespread landsliding event, which was associated with a 59-mm rainfall storm. Although the data set may be incomplete (minor shallow mass movements are typically neglected in the local records), the relative importance of precipitation prior to a storm event is evident (Fig. 7). The winter-spring storms with over 100-mm rain totals need to be preceeded by approximately 100 mm cumulative precipitation for a 15-day period in order to generate deep slope failures. For an autumn storm this value might have to be over 250 mm. There are, however, several examples of winter-spring storms, which in spite of their high event and cumulative rainfall totals, did not produce landslides.

The occurrence of deep mass movements following summer seasons is uncommon due to low antecedent moisture conditions of soils. The comparison of the three early autumn storms characterized by high intensity rainfall, and the October 1989 storm with much lower rainfall total, demonstrates that the unusually high 15- and 30-day antecedent precipitation for this event was probably critical for landsliding.

The rainfall data pertaining to six storms capable of producing mass movements are also shown in Fig. 8, where the storm durations are plotted against their cumulative rainfalls expressed as percentages of relative average monthly precipitation. The storm rainfall totals are indicated as percentages of average annual precipitation to facilitate comparisons with other environments. Meteoric events which generated deep slides and those associated predominantly with shallow mass movements are characterized by rainfall totals representing at least 10 percent average annual precipitation and exceeding 100 percent of average monthly rainfall. The May 1991 event with the most widespread shallow landsliding registered in recent years in Caramanico was related to prolonged low intensity storm (5 and 70 percent of average annual and monthly rainfall, respectively).

It is interesting to note that the 2-day September 1989 storm, which represents the highest intensity event in recent years (17 percent of average annual precipitation and over 200 percent of average monthly rainfall), did not cause immediate slope failures. Ten days later, however, the October 1989 storm (with rainfall total amounting to 13 percent of average annual precipitation, and approx. 130 percent in terms of monthly average), promoted the occurrence of the most damaging landslide in this century in Caramanico.

In summary, the examples of storm rainfalls capable of producing the large part of earthflows and complex landslides in Caramanico suggest that antecedent moisture is a more critical factor causing slope instability than the amount of storm precipitation. This conclusion is consistent with the complex hydrological setting of the study area, and in particular with the close spatial relationships existing between the mass-movement sites and the springs.

Causes and triggers of recent landsliding

Most cases of recent landslides in Caramanico can be associated with periods of high precipitation several days long. However, the definition of the exact trigger and the triggering mechanism often remains uncertain because it requires a thorough understanding of numerous local environmental factors which can promote instability. In order to illustrate the problem and to examine potential impact of man-made changes of slope environment on the distribution and timing of landslides, several examples of mass movements are reviewed in detail.

1989 landslide events

Two damaging mass movements occurred in early autumn 1989, in response to heavy and prolonged precipitation during the last decade of September and the first eleven days of October (Fig. 6). In this period, the Caramanico Terme pluviometric station registered over 400 mm of rain (Buccolini and others 1995), most of which fell during two major storms. It is interesting to note that the first one, a 4-day late-September storm characterized by a 218-mm rain total (Fig. 8), with 180-mm 24-h peak on 29 September, apparently did not generate mass movement in the Caramanico area (Wasowski 1996a). Major landsliding, however, occurred at the end of a 4-day October storm (170 mm of rain total, with 110-mm maximum on 10 October). Therefore, the occurrence of two major storms (388 mm of rain total) within a 2-week period represented a critical factor (Fig. 8).

In particular, on 10 October an earthflow of a few hundred meters long and several meters thick blocked an important road, SS 487, about 3 km south of Caramanico (Fig. 2). The movement followed the path of the F.so Casella watercourse (right affluent of the Orta river), and affected predominantly argillaceous lithologies. Subsequent field checks showed that the road mantle in this area suffers minor deformations almost every spring. Furthermore, the examination of the 1954, 1983, and 1985 air photos revealed that this area had been subject to landsliding in the past.

In the autumn of 1989, the major movements coincided with a period of intense rainfall (110 mm in 24 h); therefore, this meteoric event can be interpreted as the triggering factor. Although the lack of data precludes the reconstruction of the landslide history, the presence of the abundant antecedent rainfalls should be considered as a major contributing factor.

The second event linked to the October 1989 storm, the so-called Caramanico landslide (Buccolini and others 1992, 1995), was the largest (over 33 ha) and most destructive mass movement which has occurred in this century in the municipal territory of Caramanico Terme. This complex landslide, several tens of meters deep, destroyed over 700 m of roadways in the southern periphery of Caramanico (Figs. 1 and 2).

The 1989 Carmanico landslide remobilized the middle-lower portion of the versant capped by carbonate megabreccias several tens of meters thick (Fig. 1). This area, just south of the town's cemetery, is characterized by (1) the presence of an extremely thick sedimentary mantle (in places exceeding 40 m; Buccolini and others 1991), composed mainly of coarse to very coarse carbonate detritus most likely of debris flow origin, and secondly, of sieve-like and water-laid deposits, and reworked clay-rich materials containing carbonate clasts (debris- or earthflows), all probably originating an old alluvial fan setting (Fig. 3; Wasowski 1996a); (2) valley-ward dip of the substratum/surficial cover interface and presence of numerous pre-existing shear discontinuities within the mudstone substratum (Fig. 4); (3) relatively steep (15° on the average) and irregular surface topography, and (4) undercutting by the Orta river, which is eroding the toe of the slope.

Historical accounts confirm that this area has witnessed the occurrence of at least two important mass movements in the last four centuries (Almagià 1910; Buccolini and others 1992; Wasowski and Fiorillo 1991). Furthermore, the study of a series of air photos (from 1954, 1983, and 1985), and ground-based photographs from the mid-eighties, documented the existence of local failures and slow deformations downslope the cemetery, as well as the presence of active river erosion at the slope base. According to eyewitness accounts, the first macroscopic movements (wide cracks in the road pavement) of the 1989 landslide started in the night of 11 October at 23.30 hours, i.e., near the end of the October storm. Major deformations, with locally vertical displacements of the road of over 5 m, took place the same night. The movements continued at a rate of about 3 m/24 h for a few more days, during which no precipitation occurred. The 1-day delay between the end of the October storm and the occurrence of major displacements suggests that the role of the Orta river might also have been very important. In fact, it is possible that the timing and chronology of landslide movements are associated with a period of intensive fluvial erosion of the slope toe, in relation to the unusually high flood levels reached by the river in October 1989; it is likely that such process would produce major destabilizing effects following the maximum flood stage, i.e., towards or after the storm end.

The difficulty in identifying a single triggering mechanism from a number of possible casual hydrogeological processes is linked to the complexity of the slope groundwater regime. In particular, the presence of the interlayered succession, including deposits with low vertical permeability, and the considerable lateral extent of the versant, suggest that the predictions of the variations in the groundwater level and pore pressure in response to a meteoric event need to be based on long-term (years) piezometer data.

Furthermore, it appears that human activities, and especially the new roadcuts and large embankments made in the early seventies, have significantly decreased the stability of the slope (Wasowski and Fiorillo 1991). This might be supported by the observation that the main scarp of the 1989 slide follows the SS 487 road configuration closely uphill (Fig. 2b), and that the maximum vertical drop (up to 25 m) occurs where the scarp encounters the thickest embankment fill (just south of the cemetery, Fig. 1).

In fact, the construction of a thick embankment (locally up to 8–9 m in thickness) increased overburden of the slope. Furthermore, as stressed by Wasowski (1996a), in the cemetery area the fill material was placed across a morphologic depression characterized by the presence of an intermittent watercourse. Most importantly, it was a zone of concentrated subsurface flow as indicated by the presence of a medium discharge spring further downslope on the 1955 topographic map (Fig. 2b).

1992 landslide events

The early spring 1992 storm (9–11 April), characterized by total precipitation of 210-mm, with a 127-mm peak on 10 April (Figs. 7 and 8), resulted in several mass movements in the Caramanico area (Fig. 2b). In particular, two complex rotational slope failures, named the municipal swimming-pool and Cappuccini Monastery slides (~60 and ~50 m in length, respectively), created major damage (Wasowski 1996a). The overall displacements were limited to a few meters, and the slide depths ranged from several to less than 20 m.

The landslides occurred on urbanized slopes of the north-facing versant of the Orfento river. This versant shows scars of old slope failures, one of which, several hundred meters in length occurred in the 19th century (Buccolini and others 1995). This, and the recurrence of minor cracks and deformations on the road mantle and on the local soccer ground, imply that the slopes are marginally stable. The area affected by the two slides is covered by thick (probably 20 m) surficial materials, including fill, carbonate debris, and brecciated gypsum bodies in silty-sandy "matrix". This cover, in part of landslide origin, is underlain by a clay-rich substratum containing intercalations of evaporitic rocks.

The swimming-pool as well as Cappuccini Monastery slides are closely associated with new engineering works conducted at the two sites. The first case is related to the construction of the swimming-pool facilities, which began in 1987. Although finished 2 years later, some stability problems, aggravated by the meteoric events of early autumn 1989, prevented the opening of the pool. Due to subsequent movements, and especially those of the April 1992 slide, the facility has become operational only recently (summer 1996).

The preparatory stage of the Cappuccini Monastery slide appears to be intimately associated with the construction of a parking lot which began in early autumn 1991 in an area downslope of the road connecting Caramanico with the San Nicolao quarter. The eyewitness accounts indicated that the initial signs of slope instability occurred shortly after a $\approx$4-m-high cut was executed below the road embankment (Wasowski 1996a). The first deformations were recognized from the occurrence of fresh cracks in the road pavement, which later evolved to minor steps. The construction works were interrupted around the middle of December. In February 1992 about 80 m of the road was partially damaged, and multiple cracks with a vertical drop of up to 0.20 m were observed upslope in the monastery area. The maximum vertical displacements of the road mantle of over 1 m were reached during the storm of 9–11 April.

It appears that also the 16th-century structure of the Cappuccini monastery was damaged in relation to the spring 1992 events. Although the exact dates and measurements are lacking, the Cappuccini monks recall having observed re-opening and widening of some pre-existing cracks on the building walls in the same period (Father Cucchiella, written communication 1992).

The presence of fissures pre-dating 1992 indicated the necessity of interpreting the significance of the last mass movement in the context of the longer evolution of the site instability. The review of the monastery records showed that the first cracks occurred in the walls almost 30 years ago, in a period coinciding with the construction of a new road to the San Nicolai quarter of Caramanico (i.e., the road damaged subsequently by the 1992 landslide). In order to fit the pre-existing dirt road to traffic, some cuts were excavated, and additional embankment fill was placed to level a natural concavity just east of the Cappuccini monastery. Although this concavity had already been partially remodelled in the past by the local farmers, its elongated form in the downslope direction is still well visible on the 1954 air photos. This suggests that the origin of the depression might have been shaped by watercourse erosion or an ancient mass movement.

Thus, similarly to the case of the 1989 Caramanico landslide, the construction of the road embankment over a morphologic depression, capable of concentrating local subsurface flow, inevitably led to slope instability. The conclusion that can be drawn from this case-history is that the slope modifications realized by man in the last three decades were more determinant for the stability of the monastery building than the four hundred years of changes operated by nature.

Another minor slope failure whose 15-m-wide scarp damaged the embankment of route SS 487 (Fig. 2b), can be associated with the spring 1992 meteoric events. Although the storm of 9–11 April resulted in most macroscopic deformations (steps in the road mantle with vertical displacement up to 0.5 m), the cracks had already been observed in the asphalt pavement on 11 March. On the same day the evidence of very recent shallow (approx. depth 0.5 m) translational slides in surficial cover was noticed immediately downslope of the embankment. The exact date of occurrence of the movements is not known, but, considering the fresh appearance of the slide scars, it is likely that they took place on 9 March, following a 3-day period of modest rainfall (30 mm). This timing is also indirectly supported by the lack of rainfall in the preceeding days of March, and the presence of very low precipitations in February (26 mm). Such episodes of shallow translational landsliding in topsoil and detrital cover are quite common during the winter-spring transition.

Long-lived mass movements and widespread landsliding

In addition to the slope failures near the Cappuccini Monastery and the swimming pool, the April 1992 storm caused a considerable increase in the activity of the long-lived Pisciarello landslide; its name derives from the Pisciarello spring characterized by a modest discharge (not exceeding 1–2 l/s), and located approximately 50 m upslope of the main scarp (Fig. 2). This composite landslide of slump-earthflow type, nearly 500 m long, and up to 100 m wide, is the largest mass movement present in the vicinity of the historic center of Caramanico Terme (Wasowski 1996b). The exact depth of the basal slip surface is not known, but the overall morphology of the earthflow body suggests a thickness between 10 and 15 m.

In the last decades the landslide has shown an intermittent, if not seasonal or even continuous activity. Frequent field observations conducted since 1990 indicate that the movements of the earthflow section are very slow (probably few meters per year). Its activity is typically the highest in the early spring.

The evolution of the Pisciarello landslide has been also characterized by a significant retrogression of the main scarp, which amounted to approximately 41 m in the last 40 years (Wasowski 1996b). Furthermore, the air photo analysis and direct field measurements showed that in a period from 1989/1990 till the end of 1994 the short-term rate of scarp recession was over 3 m/year. This apparent acceleration of the retrogressive process might be linked to the prolonged and heavy precipitation of early autumn 1989. The major problem with this hypothesis is that the short-term rates of the scarp retreat are not known for the period preceeding the 1989 meteoric events.

Nevertheless, the renewal of the activity of the Pisciarello landslide in relation to the 9–11 October 1989 heavy rainfalls was reported in the local newspapers 3 days after the end of the storm. Furthermore, a comparison of the air photos from a flight flown over the area on 18 October, with those from October 1985 and October 1983, revealed much increased activity of the degradation zone in autumn 1989. Finally, a stereoscopic analysis of the October 1989 and February 1990 air photos showed that, due to several slumping episodes in this 4-month period, the scarp retreated by up to 6 m (Wasowski 1996b).

It should be noted that apart from some surface drainage works realized in the mid-fifties upslope of the Pisciarello landslide crown, no other remedial works have been made in the area until recently. Furthermore, the 1990 field controls revealed the inefficiency of the existing old surface drainage due to lack of maintenance. Only by 1994 had a portion of the old superficial drainage been repaired, and in 1995 new groundwater drainage works were constructed. The recent engineering interventions have probably led to a significant improvement in the local slope stability, as the process of scarp retrogression has slowed down since 1995.

In addition to the anthropogenic factors, the retrogressive process is sensitive to the velocity with which the Orta river erodes the earthflow toe. The erosion promotes the movement of the earthflow body and, in turn, influences the rate at which the new slide material is being removed away from the degradation zone. The resultant loss of support from the scarp base perpetuates the slope instability.

The amount of annual rainfall represents another variable that may correlate with the observed changes in the rate of the retrogressive process. Apart from the unusually high precipitations of early autumn, the 1989 annual rainfall was well above the average (Fig. 5). Furthermore, it followed two other years with high annual rain totals. Instead, after 1989, for five consecutive years a constant decrease in precipitation amount occurred. Thus, if the Pisciarello landslide behavior bears any relation to the variations of yearly precipitation, the deceleration of the retrogression process observed since 1995 might indicate a considerable delay because of the climatic change.

It is possible that the local groundwater regime, including the springs, might exhibit a similarly slow reaction to climatic factors (i.e., might be sensitive to cumulative rainfall variations of 1 year or more). The piezometric data relevant to the 1989 Caramanico landslide revealed significant variations of the groundwater table (Buccolini and others 1995), although the monitoring was conducted only for about a year. No data are available on spring discharge changes in Caramanico, and although some perennial springs are located closely upslope of the Pisciarello slide crown, any correlation between the variations in the groundwater discharge and the mainscarp recession process has yet to be demonstrated.

In addition, the meteoric and mass movement events of 1992 show that the distribution of precipitation throughout a year is also a very important factor. Frequent field controls indicated that, at least in qualitative terms, the activity of the Pisciarello landslide in April 1992 was the highest observed in the last 7 years. The explanation is quite simple: the overall precipitation of that month was exceptionally high (Fig. 6), and the rainfall totals of the storm of 9–11 April which occurred in the early spring season, are known to have increased mass-movement activity even under average meteoric conditions.

In fact, the episodes of very shallow translational landsliding are most frequent in the winter-spring period, following the two most rainy months of the year, November and December (Fig. 6). By this time the groundwater levels and spring discharges are most likely at their maximum and, where the mudstone substratum is very shallow, the overlying surficial cover may reach a complete saturation following even a modest rainfall, or possibly a rapid snowmelt. Frequent saturation implies that it will be rather difficult, and perhaps unnecessary, to establish specific rainfall thresholds for these shallow mass movements.

The following examples illustrate that mass movements are more common during the spring wet season. On the 18 October air photos, the shallow mass movements associated with the 8–11 October 1989 storm appeared less numerous than those witnessed in the spring seasons of 1991 and 1992. Furthermore, the number of shallow slope failures registered following the storm of April 1992 was lower with respect to that of spring 1991. In particular, in May 1991, after a mid-month period of rather low intensity precipitation (59 mm in 5 days), the spatial frequency of these small failures was so high (over 80 in an area of $\sim 0.25\ \mathrm{km}^2$), as to justify the term widespread landsliding (Fig. 9). In addition, several shallow mass movements, including one earthflow in the middle-lower portion of the 1989 Caramanico landslide, were noticed in January 1991, following the mid-month storm.

The conditions most favorable for the late winter-spring widespread shallow landsliding occur mainly on the WSW-facing valley side of the Orta river, in a zone which extends for about 1 km from the Pisciarello slide area to the Case Mancini area in the south (Fig. 2b). This area is characterized by the presence of several deep gullies incised in mudstone substratum (Fig. 1). The gullies floors are steeply sloping (20° on the average), and are occupied by minor and somewhat intermittent watercourses, tributaries of the Orta river. The spatial distribution of the gullies is linked to the groundwater discharge areas and springs present upslope (Fig. 2b).

Fig. 9
Widespread mass movements on May 1991 in a zone between Pisciarello landslide (just left of photo), and Case Mancini locality (group of houses in upper right corner just below route SS 487); view is to ENE; in foreground note Orta river eroding toes of gully-channeled earth and debris flows

The gullies are sites of most active erosion and the great majority of shallow mass movements, including soil slips and debris translational slides, initiate within their margins (Fig. 9). These small movements, typically a few meters in width, commonly degenerate into elongated debris flows during their further movement down the steep gully walls. In this way new material is supplied to several-meters-thick earthflows or debris flows which occupy the gully bottoms. These flows often reach the banks of the Orta river and exhibit an intermittent activity, which in part is controlled by the fluvial erosion of their toes.

Since the middle-lower valley slopes of the Orta river are not inhabited, these shallow movements do not represent a significant risk to humans. However, they result in a considerable land loss considering their seasonal recurrence and associated intensive gully erosion. Furthermore, in the long term, the process of gully headward erosion together with landsliding, if left uncontrolled, may end up damaging the lifelines situated uphill.

The recent case of the Ischio gully landslide in the Case Mancini locality (Figs. 1 and 2), is an example of problems that may occur in the future elsewhere in the zone of widespread mass movements (Wasowski 1996a). This gully, over 200 m long, develops just below the Ischio spring (hence the name), which drains the waters of the local carbonate breccia “caprock”, site of several dwelling houses. Although spring discharge is modest (2–5 l/s), its waters were used for the domestic needs of the Caramanico population since the late 1984. However, sometimes in the Spring of 1994 (the exact date is not known), probably due to a combined effect of erosion and mass-movement processes, the Ischio intake works were damaged.

One significant episode of mass movement took place in the Case Mancini area in February 1973, possibly in relation to a mid-month period of modest precipitation (57 mm in 3 days). This rotational-type slide, occurred upslope of the Ischio spring, and caused a vertical displacement of a few meters to the marginal portion of the Case Mancini carbonate caprock. According to eyewitness accounts this failure was associated with a period of widespread shallow landsliding in the surrounding area. In addition, some renewed landsliding downslope of the Ischio spring was observed in 1984 (Caramanico Terme Technical Office, written communication 1984).

Mass-movement activity apparently decreased in the Ischio area after 1984, when most of the spring waters began to be utilized for the town aqueduct (Mr. V. Silvestri, personal communication 1994). Finally, since the spring waters flow again freely into the Ischio gully, following the damage of the intake structure (winter 1994/1995), a constant increase in erosion has been observed. This situation led to the gradual revival of activity of earthflows and debris flows within the gully throughout 1995, and, subsequently, to an approximately 80-m-wide rotational slope failure in April 1996. This last episode did not coincide with any rainstorm.

The foregoing reconstruction of the events in the Ischio area demonstrates again that the human interference in the local environment can reverse the evolutionary trend of some natural processes such as erosion, and thus dramatically alter the rate of occurrence of landslide events. Even leaving aside the anthropogenic factor, the complex hydrogeological setting, and in particular, the close relation to a perennial spring and the presence of the Orta river erosion at the slope base, strongly suggest that it will be difficult to predict the timing of single episodes of retrogressive landsliding in the Ischio area in relation to specific rainfall events. Instead, considering several analogies existing between the Ischio and the long-lived Pisciarello mass movement, it might be interesting to investigate the potentially correlative response of the two phenomena to groundwater discharge variations.

Conclusions

The review of the Caramanico landsliding history illustrates some problems that may arise when trying to establish time-specific correlations between rainfall and mass-movement episodes. Some inherent difficulties may be common in the following situations.

1. On man-modified slopes, human beings, unlike many geological and geomorphological processes, are capable of dramatically altering or even reversing the course of the events leading to mass movement. The complexity of the problem is enhanced by the fact that it is often very difficult to establish how much of the recent geomorphic change, whether positive or negative for slope stability, is to be attributed to man.
2. After major modification of a slope environment by any important anthropogenic or natural event (e.g., construction of a large river dam, a high-magnitude earthquake, a large-scale mass movement), the rainfall-landsliding relationships may change significantly with respect to those known from the pre-existing records.
3. In comparison to first-time landslides, mass movements representing remobilizations of pre-existing slide bodies may be characterized by more complex hydrologic response to rainfall, because slopes with a long history of landsliding will tend to have more irregular surface and groundwater flow regimes. In particular, it will be difficult to predict partial remobilizations of slopes mantled by thick, multilayer successions of lithologically heterogenous surficial deposits (including old landslide bodies). The rainfall-mass movement relationships in these settings may depend largely on the hydraulic conductivity contrasts (Hodge and Freeze 1977), whose geometries at depth and exact contribution to slope instability can be defined only with the aid of costly subsurface investigations.
4. In marginally stable areas whose transition to actively unstable setting (cf. Crozier 1986) is controlled by several different geomorphic and physical processes, the relative importance of each destabilizing factor may be difficult to quantify; for example, the presence of intensive fluvial erosion at the slope base and perennial springs upslope may mask the expected response of slope to precipitation.
5. Long-lived landslides characterized by slow movements, incapable of generating sudden slope changes, may not be readily associated with a single triggering cause such as intensive rainfall.

Some other problems may arise from the lack of a clearly defined temporal frame for a triggerring process. For instance, in a recent proposal of a method for reporting landslide causes and triggers (Popescu 1994), the time-limits of triggering mechanisms are not quantified precisely. Should it be a process of a very short duration, as the word trigger implies (cf. Wieczorek 1996), then, for example, prolonged rainfall (several days) would be more correctly classified as one of the landslide causes rather than as a real trigger. Instead, intense short-period (~24-h) precipitation would clearly represent a good case of a hydrogeological trigger.

Obviously, the response time of slopes to precipitation will depend greatly on the permeability of surface and near-surface geologic materials. For example, the occurrence of rain-induced failures on slopes composed of low-permeability argillaceous sediments may be significantly delayed with respect to the timing of mass movements involving highly permeable unconsolidated deposits. Similarly, for a marginally stable or unstable slope, the thicker a mobilized mass, the longer the response time of the renewal or acceleration of movements will tend to be. Therefore, when examining rainfall-landslide relationships, a clear distinction ought to be made between the slope environments susceptible to shallow and deep-seated mass movements.

Any triggering process needs to be associated with an obvious measurable effect, i.e., mass movement in this case. It would probably be difficult, however, to establish practical thresholds for the acceleration of the displacement velocity in case of slow long-lived landslides characterized by short pulses of increased activity. For this type of movement prolonged periods of in situ monitoring of their evolution will be essential.

Since man is capable of both improving and worsening the stability of slopes, rainfall-mass movement relations are to be expected to be more complex in man-modified environments than in natural settings. However, because the socio-economic impact of landslides on developed slopes is most significant, the studies of hydrogeological triggering mechanisms should focus on those settings. It might be also argued that the occurence of widespread mass movements on densely urbanized slopes is either unlikely or exceptional, whereas single slope failures, or a few of them, are the most common case. Therefore, it appears that for predictive and mitigative reasons, it might be practical and advantageous to concentrate more research efforts on defining the rate and duration of causative processes which lead to an initiation or acceleration of different mass movements.

The example of this case-study indicates that in man-modified, geologically and geomorphologically complex environments, each rain-induced landslide event on a given slope site will most likely be linked to a process involving unique threshold, depending on several local destabilizing factors. Furthermore, even on a single versant scale considerable uncertainties may exist in our comprehension of rainfall-landsliding relationships. There is a risk that the results of this case-study only pertain to local events, and if transferred indiscriminately to other smaller-scale investigations, may confuse the general goal of predicting widespread landslide occurrence.

On the other hand, detailed field-based observational data, including possible results of in situ monitoring, are essential to improve the reliability of predictive models. Therefore, the regionalization of local-scale data on rainfall-mass movement relationships should rely on the results of several well-documented but simple case-studies conducted in similar physical settings (with comparable climatic and rainfall patterns, surface and groundwater hydraulic characteristics). This approach is needed to determine the relative influence of natural and human factors on slope stability, and to highlight the climatic events capable of generating mass movements on a regional scale.

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