ELSEVIER
Geomorphology 30 (1999) 65–78
GEOMORPHOLOGY

Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France)

Jean-Claude Flageollet *, Olivier Maquaire, Brice Martin, Dominique Weber

CEREG (Centre d'Etudes et de Recherches Eco-Géographique), UFR de Géographie, 3, rue de l'Argonne, 67083 Strasbourg, France

Received 27 May 1997; received in revised form 3 January 1998; accepted 29 June 1998

Abstract

Research into the climatic causes behind the triggering and reactivation of landslides has been carried out in two basins in the Southern French Alps, where a great many landslides have occurred over more than a century. Correlations between landslides and climate are sometimes precise and closely related in time, at other times imprecise and more distant. The better known the type of landslide and the date of its occurrence, the greater the correlation may appear. Be this as it may, climate is never the sole cause. This paper deals with the limits of the effects of climate.

Keywords: landslides; triggering; reactivation; relationships; climate; precipitation; Southern French Alps

1. Introduction

In recent decades, numerous studies have been conducted by various specialists (geomorphologists, geologists, civil engineers), working in the field of natural risks, into the causal relationship between climatic conditions, and more particularly precipitation, on the one hand, and landslides on the other. Among more recent studies those carried out in the framework of the two European projects TESLEC (Temporal stability and activity of landslides in Europe with respect to climate change, 1994–1996) and the earlier EPOCH (Temporal occurrence and forecasting of landslides in the European Community, 1991–1993) have made it possible to take stock of the situation at the European level, while at the same time bringing to light a series of new findings (Casale et al., 1994; Dikau et al., 1996a).

The aim of the present article is to present the findings for France's Southern Alps with regard to historical landslides, to highlight the difficulties that may be encountered with respect to the information and the correspondences to which it may give rise and to examine the reliability of the causal relationships established.

2. Test sites

Situated in the Southern French Alps (Fig. 1), the basins of Vars (Hautes-Alpes) and Barcelonnette (Alpes de Haute-Provence), separated by some 10 km, lie either side of the Massif du Parpaillon, whose highest peak is around 3000 m altitude. Completing the work of the glaciers, the torrential erosion

* Corresponding author. Tel.: +33-3-8845-6415; Fax: +33-3-8841-1359.

E-mail address: cerg@cereg-ulp.u-strasbg.fr (J.-C. Flageollet)

0169-555X/99/$ - see front matter
PII: S0169-555X(99)00045-8

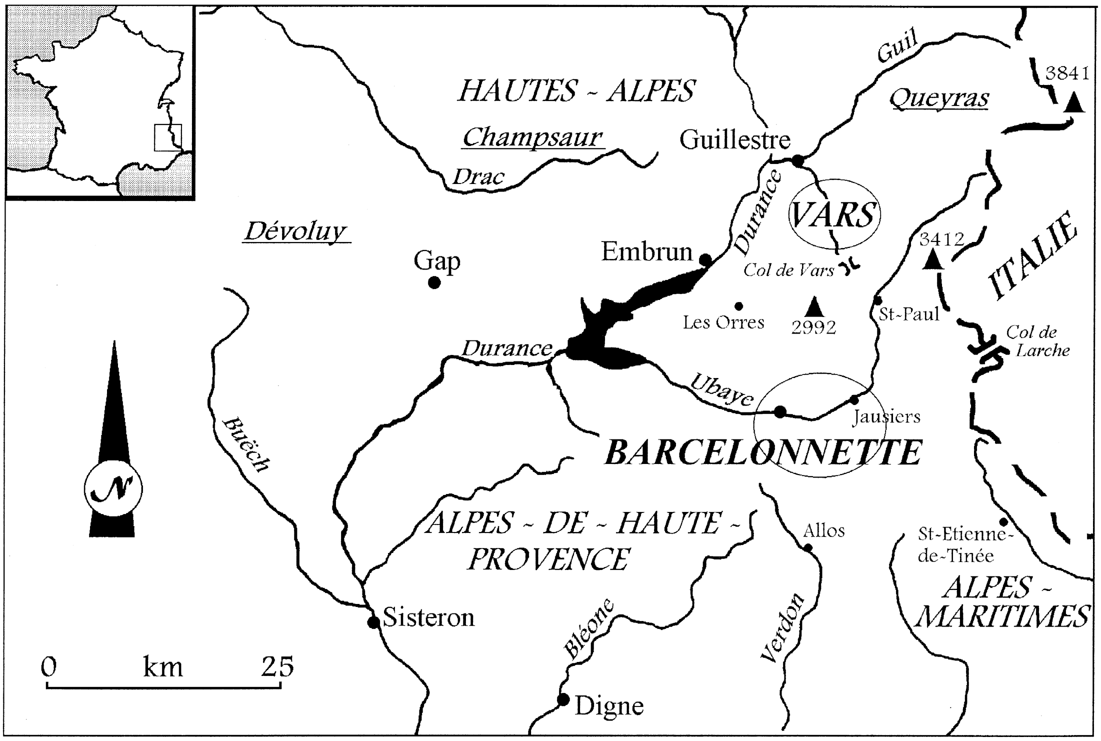


Fig. 1. The Barcelonnette and Vars basins in the Southern French Alps.

of the Chagne and the Ubaye has carved out two large gently sloping basins in the thrust sheets of the Embrunais, covering 9000 ha in the black schist of the basal complex of the Parpaillon thrust sheet at Vars, and 13,000 ha in the autochthonous black marls at Barcelonnette. Lying on an East/West axis, and widening at the mouth, the broad Barcelonnette basin slopes up from 1100 to 3000 m altitude. The relief of the Vars basin, which is situated on a South/North axis, is more jagged, lying suspended for the most part over the Guillestre depression at an altitude of between 1400 and 3300 m.

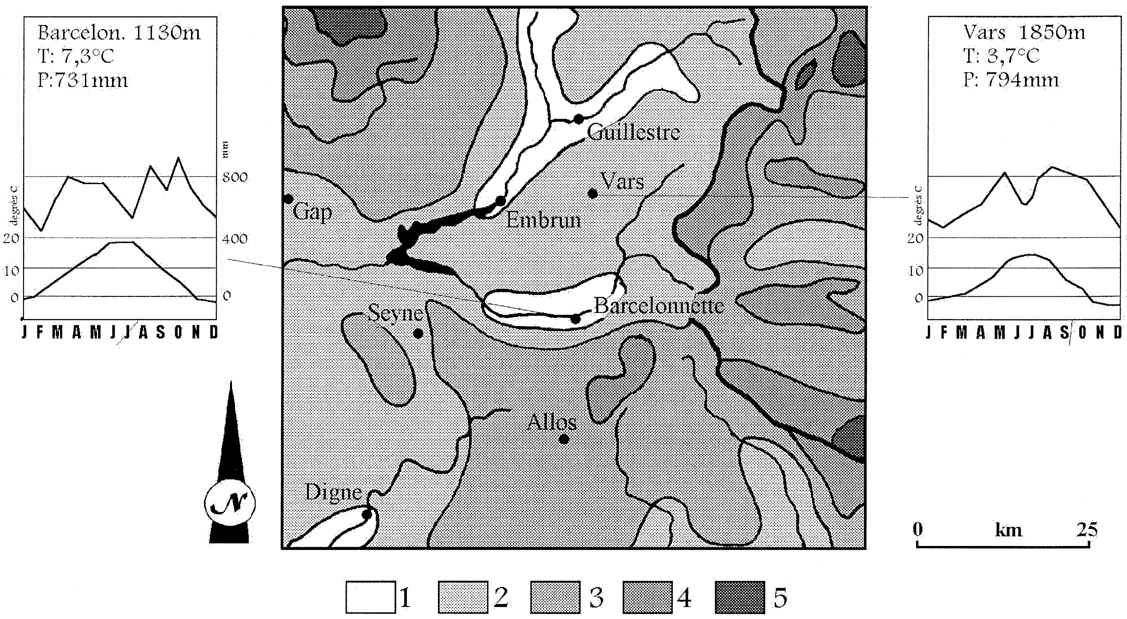
The Vars and Barcelonnette basins are particularly interesting to study from the point of view of geomorphological risks, due to the concentration of numerous phenomena in confined areas of only a few square kilometres. This ''richness'' is to be explained by the conjunction of several favourable factors including lithology, tectonics, climate and the evolving landuse (Légier, 1977; Martin, 1994, 1996; Weber, 1994).

Although the test sites are situated in the dry intra-Alpine climate zone (mean annual rainfall between 700 and 800 mm, Fig. 2) rainfall can be of a violent nature, especially during the many summer storms. On melting, the thick snow cover which forms during the cold months from December to March only adds to the effect of heavy spring rain.

3. Methodology

3.1. Data acquisition

For landslides, the study draws on well known historical research (Vogt, 1979; Fanthou and Kaiser, 1990; Pigeon, 1991; Brunsden and Ibsen, 1994; Govi and Turitto, 1994). Consultation of municipal and departmental archives enabled the identification of 132 landslides in the Barcelonnette basin since 1850 (Amiot and Nexon, 1995) and 377 in the Vars basin since the end of the 18th century (Martin, 1996). The natural hazards recorded are of various types (land-



Annual rainfall (mm):
1: < 750 mm; 2: 750 to 1000 mm; 3: 1000 to 1250 mm; 4: 1250 to 1500 mm; 5: > 1500 mm.

Fig. 2. Annual and monthly rainfall and temperatures in Vars and Barcelonnette (upper curve: monthly rainfall; lower curve: monthly temperatures). (From Evin, 1990).

slides, rockfalls, mudslides, debris flows, etc.) and various sizes (from local surface slides to complex landslides involving an entire slope). It should be noted, however, that the degree of relational probability depends on the precision of the information found in archives.

Weather stations have been providing daily information on rainfall, temperature and snow cover in Vars since 1931, in Orres, St. Paul and Jausiers since 1961 and in Barcelonnette since 1928. Before these dates, qualitative climatic information has to be obtained from archives, or deduced from dendrochronological measurements (Leroy-Ladurie, 1967; Braam et al., 1987; Assier, 1993).

3.2. The study of relationships

The degree of relational probability will vary according to the natural hazard being studied. For example, debris flow is triggered by violent, heavy rain falling in the preceding hours or days, the effect of which may be compounded by melting snow from the surrounding peaks. In the case of shallow slides or flows, the relationship may also be direct and immediate, but in many cases of major deep landslides it proves less evident, and in particular, less systematic, irrespective of the analytical time period chosen.

Working with raw rainfall data and sliding averages, in accordance with methods used by Méneroud (1983), Julian and Anthony (1994), and Pouget and Livet (1994), hazard-related climatic factors were analysed at more and more sophisticated intervals: one year or a number of years, a season or a number of seasons, different consecutive periods of several days and even 1 day. By grouping cases together, we have attempted, for different time periods, to determine thresholds triggering or reactivating landslides.

4. Results: types of climate situations and their relationship to landslides

The triggering or reactivation of landslides in the regions studied may be explained by several types of climate situation. However some landslides bear no obvious relation to climatic conditions, be they recent or more distant.

4.1. Heavy rainfall over a short period

For the most part, this type of rainfall gives rise to surface instability and debris flow-like phenomena. They are triggered immediately in the minutes or hours following the incidence of heavy rainfall, which is primarily the result of violent storms that in the space of a few minutes or hours can inundate highly localised areas with vast amounts of water.

Various authors have defined triggering thresholds for phenomena of this type (Zimmermann, 1990; Meunier, 1991). In the Ripoll area of the Eastern Pyrenees, for instance, Corominas and Moya (1996) give a threshold value of 112 mm below which shallow landslides are not triggered for rains lasting 24 h. In the upper Llobregat valley (Corominas and Moya, 1996), two recent events occurring on November 7–8, 1982 and September 8–9, 1992, where rain was absent during the previous 2 to 4 weeks, enabled the establishment of a 200 mm threshold over 24 h for shallow landslides and debris flows over a wide area. In the absence of antecedent rain, a threshold of between 160 and 200 mm over 24 h is suggested to explain the triggering of this particular type of landslide. Pasuto and Silvano (1996) provide an example of an event occurring in North Eastern Italy, which caused hundreds of landslides. After many days without rainfall, 142 mm of rain fell in 1 h (356 mm in 12 h), when hourly rainfall of 84.9 mm had been calculated for a return period of 200 years. Also in the Piedmontese region (Northern Italy) catastrophic events occurred on November 5–6 , 1994 (generalized flooding of the Po river basin with numerous large landslides) which were caused by exceptional one- and two-day rainfall amounts which exceeded all the previous historical maxima (Casale and Margottini, 1995). More recently, in the Washington State (USA), during the week of February 4, 1996, several hundred landslides of different types (mostly debris flows but also different kinds of slumps, slides and falls) were triggered in the hours and days following an exceptional climatic event (Harp, 1997): In some areas, the cumulative rainfall in 7 days reached levels of 23 in. (approx. 600 mm). Combined recordings of rainfall and the water equivalent of melted snow were locally as high as 39 in. (approx. 1000 mm). For climatic situations that are as extreme as they are exceptional, and which generate large numbers of landslides over an entire region, the thresholds are obviously exceeded, but they cannot be calculated.

Given our present state of knowledge, we do not think it possible to define triggering thresholds with any certainty for the Barcelonnette and Vars basins, primarily as a result of the lack of precise pluviometric data: the very local impact of thunder-storms and the rarity of measuring apparatus in the basins (especially at high altitudes where storms are most violent) do not enable us to determine with any precision the amounts of water effectively falling on sites triggering landslides. A similar comment could be made in respect of the precise periods of time over which rainfall is collected and measured using a pluviometer, where generally figures given relate to daily rainfall, whereas hourly measurements would provide a better correlation. A number of pluviometric totals recorded at the closest measurement station for days when overflowing was observed in Vars and Barcelonnette illustrate this point admirably (in certain cases, the previous day's rainfall is also recorded): 22.7 mm on 04/07/65; 13.2 mm on 09 and 19.7 mm on 10/08/67; 50 mm on 05 and 1.5 mm on 06/08/85; 56 mm on 08/08/86; 0 mm on 12/07/93.

Almost all events occur during the months of July and August, with others occurring in May, June and September. Although the correlation between events of this type and the day's rainfall (or day-1 according to the way in which rainfall was measured) is good, no threshold can be established on the basis of this information, due to the inadequate spatial and temporal knowledge of the rainfall.

For landslides, of all the events in respect of which the exact date they were triggered in an area that takes in the two basins is known, only one can be classified without any hesitation in the category of landslides triggered immediately following heavy rainfall over a short period. It occurred at la Salce on November 15, 1963 in conjunction with the 114 mm of rain, which fell on the municipality of Vars that same day.

4.2. Cumulative rainfall over a period of varying duration with establishment of a triggering threshold

In Vars, 104 landslides out of 134 occurred during a season including at least one month with rainfall above 100 mm. If that figure is reduced to 90 mm, 124 landslides, i.e., 92% fall into this category. All these months with a total over 90 mm are also characterised by one or several 10-day periods with rainfall above 50 or 60 mm (Martin, 1996). In the Barcelonnette basin, the landslide of May 26, 1971 was triggered following a rainy, but not exceptional, 10-day period (almost 50 mm), the last two days of which totalled 30 mm. The accumulated rainfall for the previous month was 108 mm. This rainfall fell during a very wet spring (265.5 mm between March 14 and May 26 in Barcelonnette) coming, in turn, after a winter with much snow. Another landslide occurred on June 28, 1958: cumulative rainfall for the previous month totalled 103 mm, with a final peak of 60 mm over the last 4 days, of which 30 mm fell on the 26th alone.

The number of landslides that can be dated with enough precision in the Barcelonnette and in the Vars areas is too small to be able to establish a statistical triggering threshold. Rainfall in the month preceding the landslide would however seem to play a major role, together with rainfall recorded during the last 10-day period. Pluviometric configurations of this kind are particularly conducive to landslide reactivation.

In the Eastern Pyrenees, moderate intensity rainfall has been found to trigger, and more often, reactivate mudslides and both rotational and translational slides have been observed on clay and silt–clay formations (Corominas and Moya, 1996). It seems that more than 100 mm of antecedent rain is needed before 60–70 mm rainfall over a 24 h period will lead to reactivation. Less antecedent rain is needed in the case of higher daily rainfall amounts.

Different thresholds of cumulative rainfall have been established for up to 120 days prior to 150 landslides occurring in the Cordevole river basin in NE Italy since 1920 (Pasuto and Silvano, 1996). They have notably shown a close correlation between landslide events and cumulative rainfall over a 15 day-period prior to the event, with a peak of final rainfall in the last 24–48 h before failure. In the Montaldo region of Italy, Sorriso-Valvo et al. (1994) have highlighted the relationship between the triggering of a landslide and an amount of rain in the region of 530 mm over a previous 50 day period in respect of different types of landslide.

Méneroud (1983), in his study of landslides in the Nice–Menton region analysed rainfall over five day periods to explain the piezometric fluctuations and the triggering of landslides. This type of study is generally restricted to the monitoring of slopes equipped with measuring instruments in order to model their behaviour with greater accuracy (Pouget and Livet, 1994).

4.3. Cumulative rainfall over a period of varying duration without identification of a triggering threshold

Highly diversified climate situations can also lead to the emergence of landslides without it being really possible to detect a given structure of antecedent rainfall. A qualitative approach is then adopted, and we speak of periods (generally years and months) of excess rainfall and of rainfall shortages.

In Barcelonnette, certain wet years or multiannual periods of excess rainfall are found to coincide with years in which many landslides occurred, for example, 1960, 1977, 1959–1965 and 1975–1981. If we consider the curve of annual rainfall this century (and the associated curve of 3-year sliding averages), it is possible to detect cyclical variations over a period of 15–20 years (Fig. 3). These major fluctuations reveal periods of 6–7 years of excess rainfall in comparison with the average of 721 mm established for the period 1928–1994. The most recent such period occurred at the end of the 1970s and the beginning of the 1980s. The two biggest landslides in the Barcelonnette basin were extremely active during or at the end of this period of excess rainfall: La Valette landslide occurred in 1982 (cf. Section 4.4.) and in Super-Sauze a major movement took place between 1978 and 1982 (cf. Section 5.1.1.).

Conversely, however, certain ''landslide-rich'' years are also years or multiannual periods of rainfall shortage, as was the case in 1964, 1982–1990.

Similarly, for monthly rainfall (Fig. 4) there is no systematic correlation, although some cases are associated with the heavy rainfall of the previous month

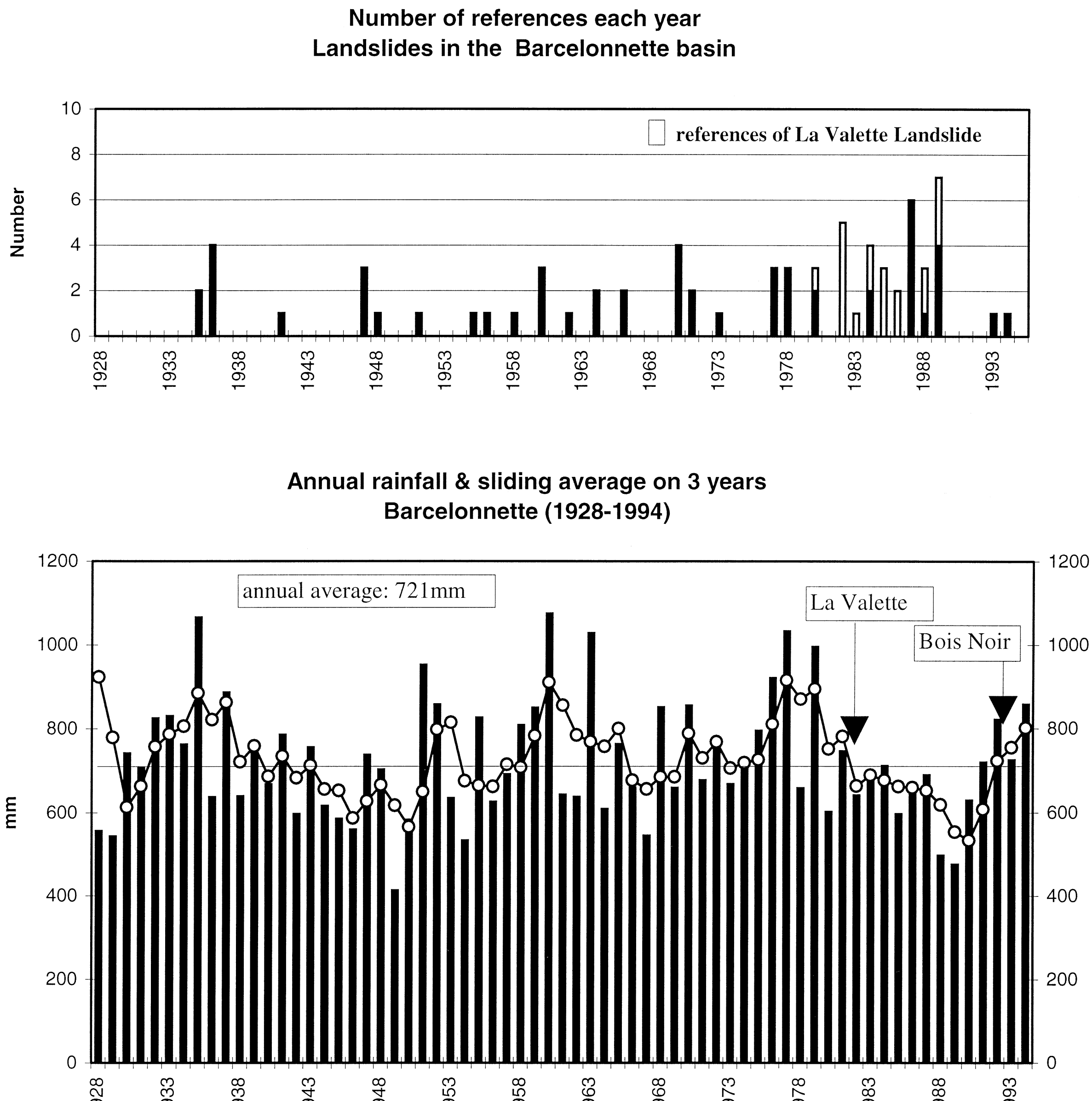


Fig. 3. Annual rainfall and references of landslides in the Barcelonnette basin between 1928 and 1994.

or months (October 1997, winter 1977–1978, June 1983 or October 1960).

Sometimes, a pattern will emerge when distant (multiannual) factors are combined with more recent (seasonal or monthly) parameters, whereby their effects are superimposed, making it difficult to estimate their respective part in triggering a landslide. In the Barcelonnette basin, the Bois Noir landslide occurred in the spring of 1993 following five autumn–winter months which were particularly low on rainfall, but after a year, 1992, of excess rainfall following on after 10 years of insufficient rainfall (Fig. 3).

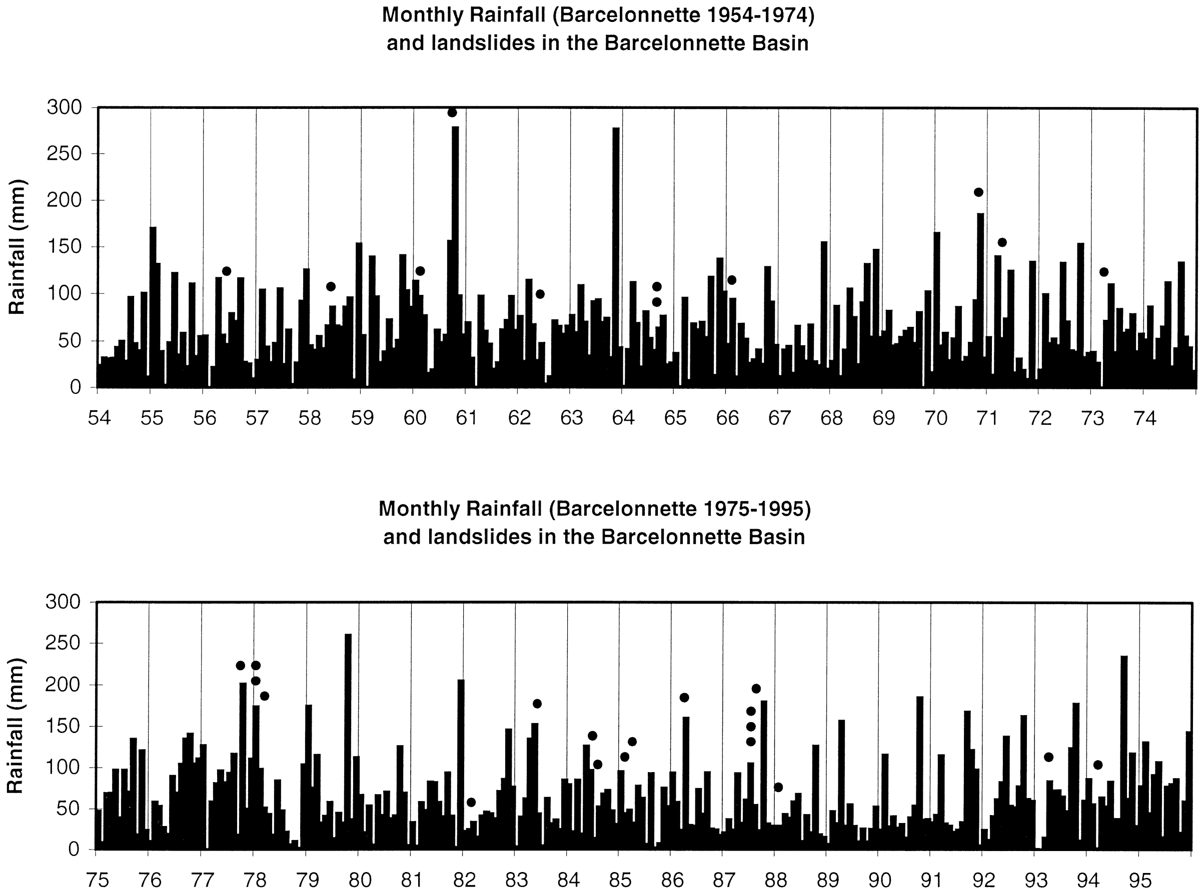


Fig. 4. Monthly rainfall and landslides in the Barcelonnette basin.

In Vars also, several landslides occurred during the spring of 1993, including two reactivations of large-scale landslides.

The seasonal climatic influence on landslides, and in particular large-scale landslides, is generally acknowledged by most authors (Vibert, 1987; Capecchi and Foccardi, 1988; Matichard and Pouget, 1988). In the Southern French Alps, the historical study of hazard occurrence leads us to the same conclusion, a wet spring season undeniably favouring instabilities. In the Vars basin, for example, 78% of the landslides recorded occurred during a wet spring. In order to further refine the analysis, three successive autumn (A), winter (W) and spring (S) seasons were investigated. The configurations that proved most conducive to landslides, in order of decreasing importance, were AwWwSw (36% of recorded cases), AwWdSw (20%), AdWwSw (13%) and AdWdSw (9%). W (wet) refers to a season characterised by higher than average rainfall, and d (dry) to a period where rainfall is below average.

4.4. Limits of the climate-landslides relationship

As the ‘‘Détection et Utilisation des Terrains Instables (D.U.T.I.)’’ report (Ecole Polytechnique Fédérale de Lausanne (EPFL), 1985) suggests, the correlation between rainfall and landslides does not always produce tangible results, especially in the case of deep, large-scale landslides.

The landslide at La Valette near Barcelonnette occurred in March 1982. It is generally acknowledged by a number of authors (Evin, 1990; Colas and Locat, 1993) that it was the consequence of heavy spring rain falling on top of melting snow. In fact, it would appear that the climatic conditions immediately preceding the triggering of the landslide were those of several cold winter months with little rainfall following heavy snowfalls in the month of December. Warmer temperatures at the end of March marked the beginning of the snow melt, combining with low rainfall (Fig. 4). As for more distant climatic conditions (Fig. 3), in the course of the last 50 years two periods of 6–7 years can be observed with above average sliding averages over three years, 1959–1965 and 1976–1981. The La Valette landslide occurred after the second period.

The climatic conditions preceding the triggering of this landslide are therefore in no way exceptional, both with respect to the rainfall of previous months or years and the temperature, which goes against accepted wisdom. We must therefore look elsewhere for an explanation of the causes behind the triggering of this landslide such as the progressive weathering and rupture of the marls, or even seismic shocks, since two earthquakes did indeed occur a few kilometres away from the Barcelonnette basin on March 8 and 25, 1982, with respective magnitudes of 2.8 and 2.7. On the other hand, the later evolution and reactivation phases correlate fairly well with rainfall, in particular in April 1989 (Colas and Locat, 1993).

Other examples are given for Sicily (Sorriso-Valvo et al., 1994) where a very marked increase in the number of landslides occurring between 1931 and 1939 bears no obvious relationship to climatic conditions. The same thing is true in Central Italy for other periods studied.

5. Discussion

In the area under study, the results obtained with respect to the relationship between climate and landslides are sometimes vague and uncertain. We need therefore to examine two points in greater detail: the reliability and quality of the relationships established between climate and landslides, and the effective part played by climate alongside other factors known to be responsible for landslide occurrence.

5.1. Reliability and quality of the climate-landslide relationship

If it is to be considered representative and reliable, any analysis must satisfy a certain number of conditions in relation to landslides and climate, but also landuse and human action. These include the quality and precision of the basic information (location, description and date of hazard, climatic data, etc.) and the knowledge of the type and age of the landslide.

5.1.1. Quality of information

The collection of information is a crucial phase, since all further analyses will depend on the initial ‘‘quality’’ of these basic data. This quality is directly and essentially a function of the information source, the nature of that information, but also the way it is gathered and retranscribed.

For a description of the phenomenon and the date it was triggered, information may be of various kinds.

– Information inferred from dating techniques such as dendrochronology, or from comparisons of maps and photographs, with only very relative precision as to landslide occurrence. The date of an event cannot be exactly determined within a period of several months corresponding to the growth period of trees or within a period of several years between the updating of different documents. The historical evolution of Super-Sauze landslide was reconstructed over the last 50 years through different sets of aerial photographs: the major movement affecting the crown of the landslide could be detected between 1978 and 1982, unfortunately without more precision by this method. In Vars, Martin and Weber (1996) calculated the progression of the Ruinas landslide in the last 165 years by comparison between the 1830 land register and present time geodetic measurements.

– Historical events described in various documents (public archives, regional press, publications, technical reports, etc.) using appropriate methods of investigation (‘‘oil mark’’ method, Vogt, 1979), systematic and exhaustive investigation of chronological series, etc.). Precision may vary widely as a function of the origin and contents of the documents, the scientific rigour with which they are gone through, the criticism and selection of information. A first difficulty arises from the unprecise temporal and spatial description of landslide events in the literature. Ambiguity of terminology is also a major drawback in relation to a number of documents, especially the older ones. Apart from descriptions found in precise technical reports, landslides are often described by non-specialists, especially in the press. The term employed is not always appropriate to the phenomenon observed. Even when precise descriptions are given, the researcher must check and rectify them in order to classify the event in the appropriate hazard category. That was for example the case of the hazard which occurred near Barcelonnette on April 12, 1939, described in the local newspaper with three different words: ‘‘mudflow’’, ‘‘rock avalanche’’ and ‘‘slide’’.

– Recent events, known with great precision, the evolution and various reactivation phases of which are monitored on the basis of ad-hoc or continuous measurements: surface and/or in depth displacements, fluctuations of the water table(s), constraints, climatic conditions. The aim being that of the accurate modelling of landslide behaviour. In Super-Sauze, landslide surficial displacements have been periodically measured in relation with rainfall since 1991: in Autumn 1994 for example, the important rainfall in September (near to 250 mm) lead to noticeable movements during the two following months (Fig. 5).

In different cases such as these, the date will be known: to the nearest year or period of years, to the nearest month or season, to the nearest day, hour or even minute. As a corollary, the same degree of precision is required for climatic conditions.

For climatic conditions in European Community countries there is in general a network of meteorological stations at regional level at least, which records different parameters on a permanent basis (rainfall, temperature, sunshine, wind velocity and direction). This network is supplemented by more local climate stations that only record rainfall and temperature. However, in mountain regions, where most landslides occur, the geographical distribution and density of such climatological measuring stations are rarely sufficient to accurately reflect the spatial variability of rainfall, even at the level of a

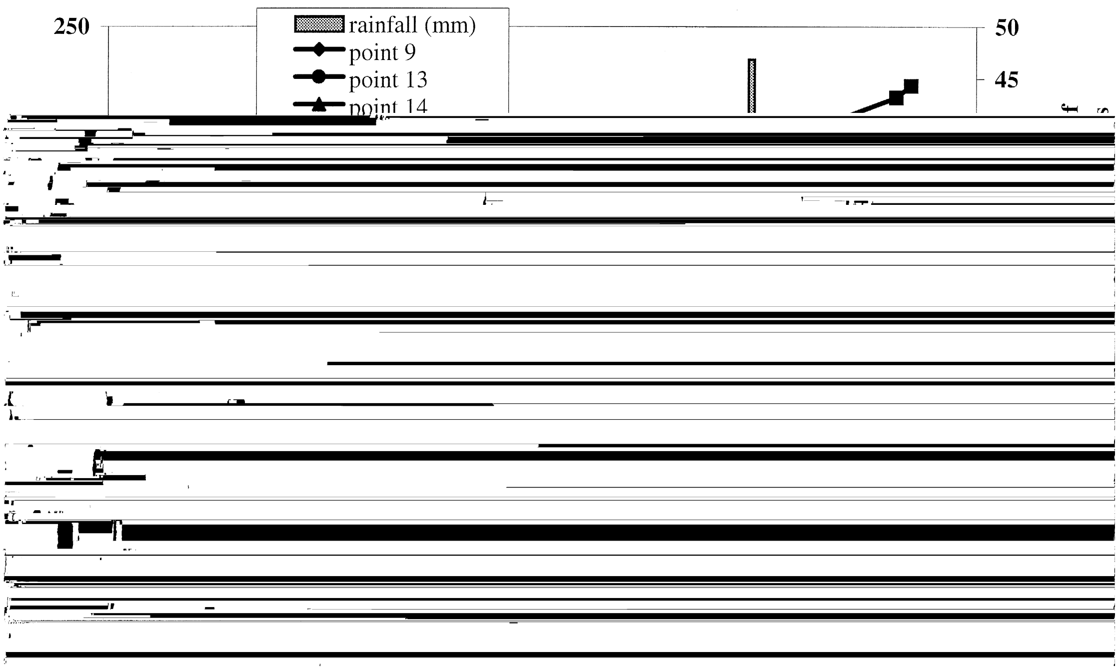


Fig. 5. Rainfall and surficial displacements on Super-Sauze landslide between 1991 and 1995.

basin of several square kilometres. This is the case in the Barcelonnette basin, where the two climatological stations of the official Météo-France network are 8 km apart and both situated at the bottom of the valley. Therefore, two supplementary and more complete stations were installed, near Super-Sauze landslide, the first in 1994 and the second in 1996. One of the main inconveniences of the insufficient raingauge distribution is the bad recording of summer thunderstorms: for example, the storm rainfall located in the upper parts of northern slopes of the basin, and responsible of an important debris flow occurred in Faucon on August 19, 1996, which cut the main road of the valley 3 km east Barcelonnette for several hours, was not registered by the raingauges, either in Barcelonnette, or in Jausiers.

For some of the oldest stations, data reach back over more than 100 years. However, these data sets often include gaps of a few days to a few years. Different statistical methods can be applied to reconstruct these missing data using those from other stations (Centre Technique du Génie Rural des Eaux et Forâats (C.T.G.R.E.F.), 1979; Givone, 1987). Some monthly rainfall figures for Barcelonnette were thus extrapolated from the Jausiers data with correlation coefficients of between 0.78 and 0.84 for summer months and over 0.90 from September to January.

5.1.2. Types and age of landslides

Landslides are very variable in form: rotational, translational, composite, complex, rockfalls, mudslides, debris flows (Flageollet, 1987; Dikau et al., 1996b), in intensity: volume, displacement velocity etc., and in the nature and behaviour of the terrain: slope, depth of surface cover, permeability, plasticity, resistance, etc. The very diversity of the phenomena under study tells us that the conditions triggering them cannot be uniform. For deep slides, it is the analysis of rainfall over previous weeks or months (and the resulting piezometric variations) which need to be taken into account, whereas for surface mudslides it is the intensity and quantity of rain falling over previous days and hours that is most relevant.

A distinction should also be drawn between landslides triggered for the first time and those which are reactivated. The climatic conditions which are conducive to triggering or reactivation of a landslide are not necessarily the same. Generally speaking, it is commonly found that for slopes that are certified as unstable there is more of a direct link between the phases of reactivation and climatic conditions (amounts of rainfall, temperature, snow melt etc). This is the case for the La Valette and Super-Sauze landslides, where measured surficial displacements are closely related to cumulative amounts of rainfall (Fig. 5).

5.2. The responsibility of climate in landslide occurrence

We have seen that if climatic conditions are generally conducive to the onset of instability, they are not enough in themselves. We should therefore guard against any overhasty attempt to establish a cause and effect relationship. The relationship between the triggering of landslides and climate parameters is therefore not always obvious and direct.

5.2.1. The seasonal problem

Effective rainfall following a period of rain will depend for the most part on sunshine, temperature and plant cover. According to the season and lie of the land, the consequences of a period of rain on the moisture content of soil will vary. In mountain regions in the springtime, amounts of rainfall can combine with considerable amounts of melting snow, so temperature must be included in the analysis. In influencing the proportions of water runoff and seepage, seepage velocity will vary widely as a function of plant cover and the degree of saturation of surface layers. These will affect the level of the water table and the response time between any increase in level and a period of rain. This response time will of course also vary according to the depth of the water table. In the Super-Sauze landslide for example, with a ground surface of black marls without vegetation, the response time of the 80 to 90-cm-deep water table is between one to 2 h after rainfall (Fig. 6).

Finally, looking beyond climatic conditions, there is a whole series of other factors responsible for the triggering of landslides: seismicity, landuse, human action are all elements that determine the initial

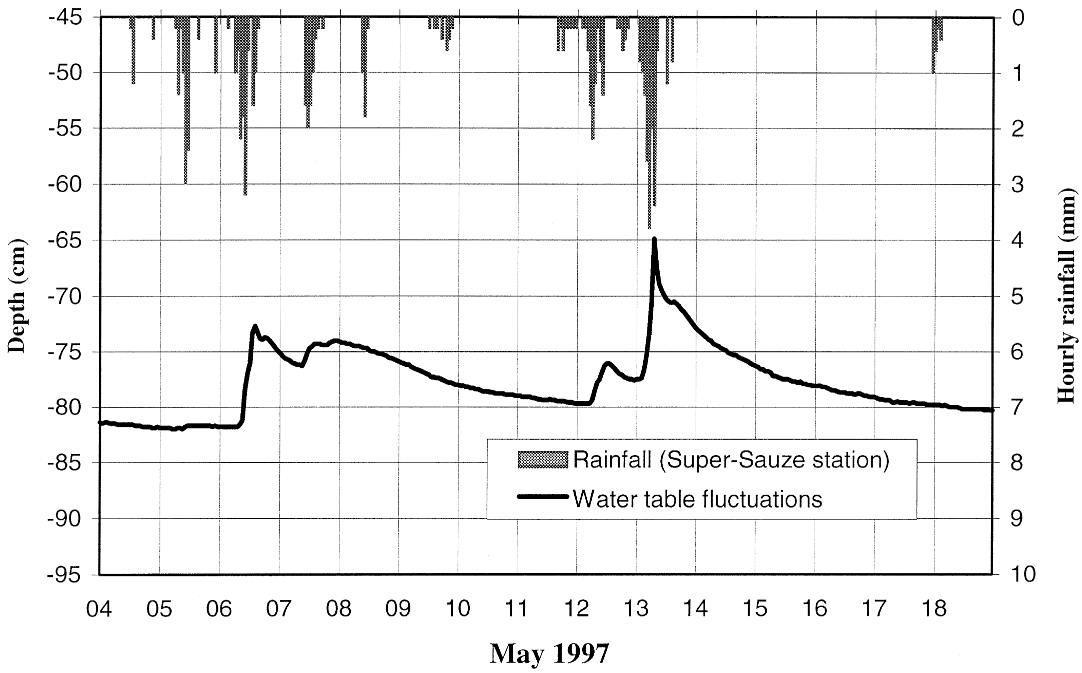


Fig. 6. Water table fluctuations in response to rainfall in Super-Sauze landslide.

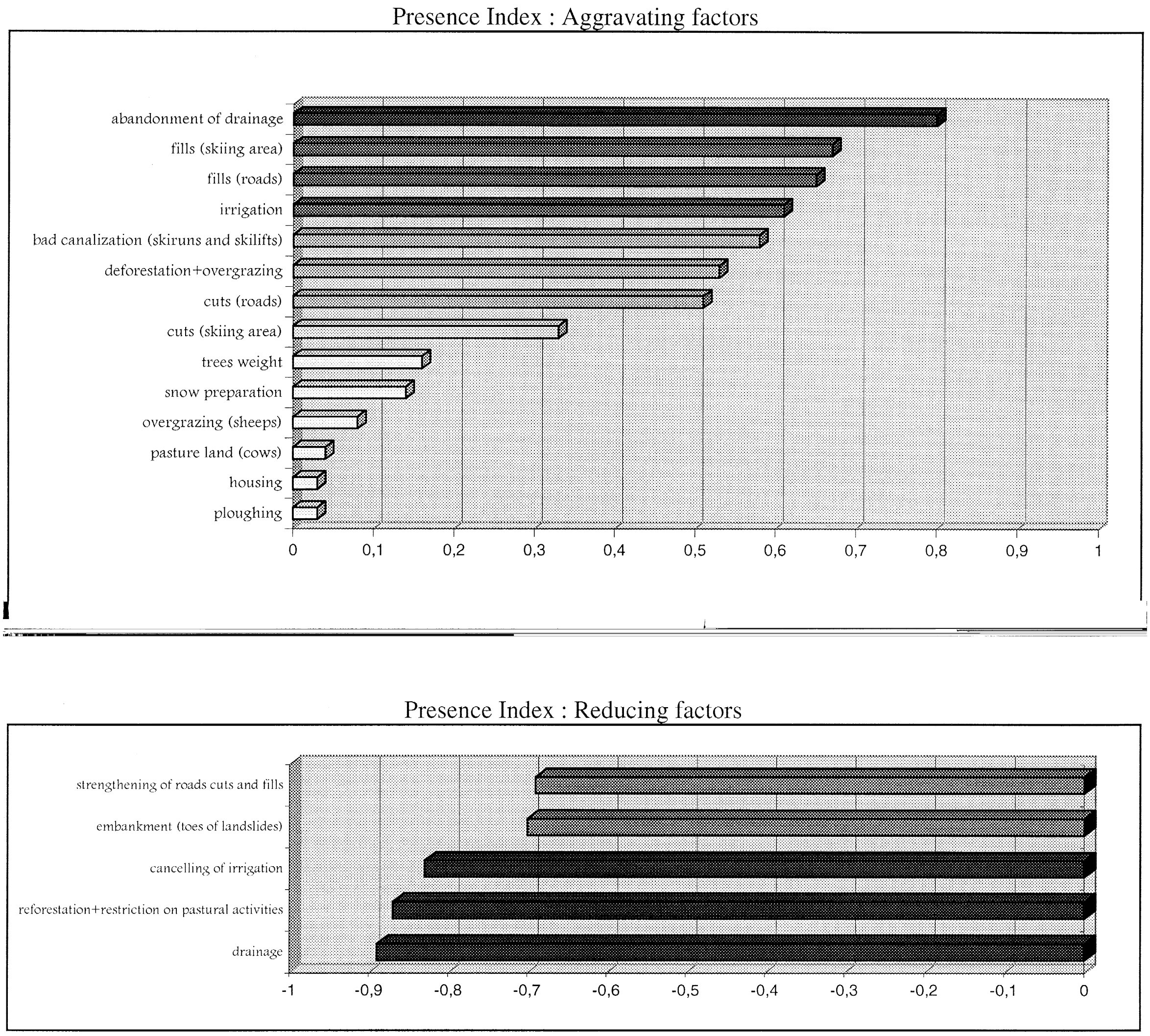
degree of stability of a slope where a landslide could occur, or has already occurred.

5.2.2. Landuse and human action

A human action can directly trigger a landslide, an excavation in a slope for road widening for example. But most human action and landuse are generally considered to increase liability to landsliding, the real triggering factors being the rainfall or the seismic events. In Vars, the study of the relationships between landuse, human activity and landslides (Martin, 1996) shows that only 7% of the 327 different events counted between 1820 and 1995 are not linked with a human factor: the most marked human-induced influences aggravating earth movements are road laying and widening, excessive irrigation, abandonment of drainage and consequent disorganisation of flows, installation of ski slopes (terracing, tracks), and destruction or bad maintenance of forests (Fig. 7). But this study shows also that, mostly, these factors alone are not able to trigger landslides, and that they take place in combination with climatic or sometimes seismic factors. On the other hand anthropogenic actions can also act in favour of landslide stabilization, as reforestation for example in Vars; they are then considered as reducing factors.

5.2.3. Initial degree of slope stability

The degree of stability is the result of all the above-mentioned factors which have an effect on a given terrain. It accounts for a major part in the relationship between the triggering or reactivation of a landslide and climatic parameters. Slope stability varies in the course of the year and is expressed in terms of a safety factor (F) which depends on external factors (effective rainfall, landuse, seismic shocks, plant cover, etc.), to which are added the massif's internal parameters: geometry and nature of the different strata, constraints, stress evolution, but also material characteristics (fatigue, cohesion evolution) and the nature of underground flows (presence of a free or confined aquifer). In the case of a slope with a precarious balance (safety factor close to one), it is enough, for example, for a slight increase in interstitial pressure following seepage of recent low rainfall to worsen an already critical situation and lead to instability ($F < 1$). Conversely, for a slope



NB: Each type of land-use is characterized by an index of presence (ratio of sectors where hazards are mentionned to the total number of sectors in the Commune), which can be positive (aggravating factors) or negative (reducing factors). Sectors are those of the land registry.

Fig. 7. Human factors aggravating or reducing landslides activity in Vars.

with a safety factor not as close to one, a sharp drop in the co-efficient value in conjunction with very heavy rainfall can lead either to a certified instability (direct cause and effect relationship) or to a precarious equilibrium, with or without the later onset of instability. For a given recent or distant climatic event, the result will therefore vary according to the initial safety factor value. Unfortunately, this is an unknown or rarely mentioned parameter in reports on historical landslides.

6. Conclusion

In France's Southern Alps, at a regional level a wide diversity is to be found in the relationships between the different types of landslide recorded and climatic conditions, giving rise to a number of complex combinations. As frequently observed elsewhere, rainfall is one of the elements of the system that accelerates or triggers landslides, together with other factors, such as landuse, for example. Generally, however, it is by far the most important element of the system.

Instability can even occur following relatively dry months, whether or not they are preceded by heavy annual rainfall. Conversely, heavy rainfall a few days, or some ten days, earlier can be enough to trigger instability even if little rain has fallen over the preceding years. The type of landslide, of course, plays a fundamental rule in this relationship.

The complexity of relations between landslides and climatic conditions makes it difficult to define ''universal laws''. Before that happens, further investigation is needed into such relations in a given area, taking into account types of landslide, their generation (triggering or reactivation), the season they occur and, finally, the resulting initial degree of slope stability.

References

Amiot, A., Nexon, C., 1995. Inventaire des aléas dans le bassin de Barcelonnette depuis 1850. Mémoire de maîtrise de géographie. Université Louis Pasteur, Strasbourg, France, 173 pp. + annexes.

Assier, A., 1993. L'englacement des Alpes du Sud franco–italiennes du petit âge de glace à la fin du XX^{è} siècle. Thèse de Doctorat de géographie, Université J. Fourrier, Grenoble 1, France, 487 pp.

Braam, R.R., Weiss, E.E.J., Burrough, P.H., 1987. Dendrogeomorphological analysis of mass movements: a technical note on the research method. Catena 14, 585–589.

Brunsden, D., Ibsen, M., 1994. The nature of the european archive of historical landslide data, with specific reference to the United Kingdom. In: Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), Temporal Occurrence and Forecasting of Landslides in the European Community 1, pp. 21–70, final report.

Capecchi, F., Foccardi, P., 1988. Rainfall and landslides: research into a critical coefficient in an area of Italy. In: Bonnard, C. (Ed.), Comptes-Rendus du 5ème Symposium international sur les glissements de terrain Lausanne, Balkema, pp. 1131–1136.

Casale, R., Margottini, C. (Eds.), 1995. Meteorological events and natural disasters: an appraisal of the Piedmont (North Italy) case history of 4–6 November 1994 by a CEC field mission. European Commission Report. 96 pp.

Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), 1994. Temporal Occurrence and Forecasting of Landslides in the European Community. European Community, Programme EPOCH, Contract 90 0025, Final Report, EUR 15805EN, 2 Vol., 959 p.

Colas, G., Locat, J., 1993. Glissement et coulée de La Valette dans les Alpes de Haute-Provence: présentation générale et modélisation de la coulée. Bulletin de liaison Laboratoire des Ponts et Chaussées (187), 19–28.

Corominas, J., Moya, J., 1996. Historical landslides in the Eastern Pyrenees and their relation to rainy events. In: Chacon, J., Irigaray, C., Fernandez, T. (Eds.), Landslides A.A. Balkema, Rotterdam, pp. 125–132.

Centre Technique du Génie Rural des Eaux et Forâats (C.T.G.R.E.F.), 1979. Estimation d'une durée de retour à partir d'une série très courte. Informations techniques, cahiers 36, No. 5, 30 pp.

Dikau, R., Schrott, L., Dehn, M., Hennrich, K., Rasemann, S. (Eds.), 1996a. The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC). European Community, CEC Environment Programme, Contract no. EV5V-CT94-0454, Final report, Part II, National Reports, 408 pp.

Dikau, R., Brunsden, D., Schrott, L., Ibsen, M.-L. (Eds.), 1996. Landslide Recognition: Identification, Movement and Causes Wiley, Chichester, 251 pp.

Ecole Polytechnique Fédérale de Lausanne (EPFL), 1985. Rapport final du projet d'Ecole D.U.T.I. ''Détection et Utilisation des Terrains Instables''. EPFL, Suisse, 229 pp. + annexes.

Evin, M., 1990. Les risques naturels dans un espace montagnard: la haute–Ubaye. Revue de Géographie Alpine 123, 175–192.

Fanthou, T., Kaiser, B., 1990. Evaluation des risques naturels dans les Hautes-Alpes et la Savoie: le recours aux documents d'archives et aux enquêtes. Bulletin de l'Association des Géographes Français 4, 323–341.

Flageollet, J.-C. (Ed.), 1987. Les mouvements de terrain et leur prévention Masson, Paris, France, 224 pp.

Givone, C., 1987. Analyse statistique d'épisodes pluvieux en zone de montagne. Mémoire de D.E.A. de l'Ecole Nationale de Météorologie, Toulouse, 85 p.

Govi, M., Turitto, O., 1994. Ricerche bibliografiche per un catalogo sulle inondazioni, piene torrentizie e frane in Valtellina e Valchiavenna. Consiglio Nazionale delle Ricerche, Geoingegneria Ambientale e Mineraria, Anno XXXI, 4, Turin, Italy, 4 Vol., 249 pp., 25 pp., 52 pp., 16 pp.

Harp, E.L., 1997. Landslides and landslide hazards in Washington State due to February 5–9, 1996, storm. U.S. Geological Survey Administrative Report, http publication, 23 pp.

Julian, M., Anthony, E.J., 1994. Landslides and climatic variables with specific reference to the maritime Alps of Southeastern (France). In: Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), Temporal Occurrence and Forecasting of Landslides in the European Community, Final Report 1, pp. 697–721.

Légier, A., 1977. Mouvements de terrain et évolution récente du relief dans la région de Barcelonnette (Alpes de Haute Provence). Thèse de Doctorat de géologie, Grenoble, 163 pp.

Leroy-Ladurie, E., 1967. Histoire du climat depuis l'an mil. Flammarion, 376 pp.

Martin, B., 1994. The role of landuse and rainfall in the triggering of landslides at Vars (Hautes-Alpes, France). In: Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), Temporal Occurrence and Forecasting of Landslides in the European Community, Final Report 1, pp. 235–319.

Martin, B., 1996. Les aléas naturels à Vars (Hautes-Alpes, France), le rôle des facteurs naturels et des facteurs anthropiques dans leur occurrence et leur évolution de 1800 à nos jours; Thèse de Doctorat de Géographie, Université Louis Pasteur, Strasbourg I., 583 pp.

Martin, B., Weber, D., 1996. Vitesses de déplacement des mouvements de terrain à Vars (Hautes-Alpes, France): le recours aux archives et à la topométrie. Revue de géographie Alpine: Les processus d'érosion en milieu montagnard, bilans et méthodes, No. 2, Tome 84, pp. 57–66.

Matichard, Y., Pouget, P., 1988. Pluviométrie et comportement de versants instables. In: Bonnard, C. (Ed.), Comptes-Rendus du 5ème Symposium international sur les glissements de terrain, Lausanne 10–15 juillet Balkema, Rotterdam, pp. 725–730.

Méneroud, J.-P., 1983. Relations entre la pluviosité et le déclenchement des mouvements de terrain. Bulletin de Liaison du Laboratoire Central des Ponts et Chaussées 124, 89–100.

Meunier, M., 1991. Eléments d'hydraulique torrentielle. Etude du CEMAGREF, série Montagne 1, 278 pp.

Pasuto, A., Silvano, S., 1996. Rainfall as a triggering factor of mass movement. Proc. of XXI General Assembly of European Geophysical Society. The Hague, The Netherlands, 6–10 May 1996.

Pigeon, P., 1991. L'homme face au risque lié aux glissements de terrain dans le masif prealpin du Chablais et son piémont (1860–1890). Thèse de géographie, Univ. de Grenoble 1, 350 pp.

Pouget, P., Livet, M., 1994. Relations entre la pluviométrie, la piézométrie et les déplacements d'un versant instable (site expérimental de Sallèdes, Puy-de-Dôme). Collection ''Etudes et recherches des laboratoires des ponts et chaussées'', série géotechnique GT57, 132 pp.

Sorriso-Valvo, M., Agnesi, V., Gulla, G., Merenda, L., Antronico, L., Di Maggio, C., Filice, E., Petrucci, O., Tansi, C., 1994. Temporal and spatial occurrence of landsliding and correlation with precipitation time series in Montalto Uffugo (Calabria) and Imera (Sicilia) areas. In: Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), Temporal Occurrence and Forecasting of Landslides in the European Community, Final Report 2, pp. 825–869.

Vibert, C., 1987. Apport de l'auscultation de versants instables à l'analyse de leur comportement: les glissements de lax en Roustit (Aveyron) et Saint-Etienne de Tinée (Alpes Maritimes). Thèse Ecole des Mines de Paris, 206 pp.

Vogt, J., 1979. Les tremblements de terre en France, mémoire du BRGM no. 96, 220 pp.

Weber, D., 1994. Research into earth movements in the Barcelonnette basin. In: Casale, R., Fantechi, R., Flageollet, J.-C. (Eds.), Temporal Occurrence and Forecasting of Landslides in the European Community, Final Report 1, pp. 321–336.

Zimmermann, M., 1990. Debris flows 1987 in Switzerland: geomoephological and meteorological aspects. Hydrology in Mountainous regions, II—Artificial reservoirs; water and slopes. proceedings of two Lausanee symposia, August 1990. IAHS Publ. 194, 387–393.