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Occurrence of landslide events and the role of climate in the twentieth century in Calabria, Southern Italy

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Abstract

A methodological approach based on analysing landslides that occurred over a long period and climatic data characterising that period is presented. The method investigates whether there are any effects of climate on landslide triggering. The approach has been tested in Calabria (Italy). Both landslide and climatic data have been obtained from available databases that have been expanded. Landslide data came from historical archives and newspapers, while the climatic analysis is based on daily and monthly series of rainfall and temperature. The method simplifies the comparative analysis of several time series by defining some indices (the monthly, bi-monthly, and … *m*-monthly indices of precipitation, temperature, wet days and precipitation, and the monthly landslide number) that can be used to study phenomena, such as landslides, that are characterised by spatial and temporal variability.

For Calabria, the number of landslides is correlated to monthly precipitation, wet days and precipitation intensity. Thus, landslide occurrence could be roughly forecasted using these climatic data. Despite the favourable climatic trend, landslides are not decreasing because the recent utilisation of landslide-prone areas increases the vulnerability.

Keywords: Landslides, climate change, Italy.

Precipitation has increased (by about 1% per decade) in the 20th century over most mid- and high latitudes of the continental Northern Hemisphere, and there has been a 2-4% increase in the frequency of heavy precipitation in the second half of the century (IPCC 2001). The winter rainfall percentage seems to increase largely due to the increasing frequency of extremely wet seasons in the case of Europe (Palmer & Räisänen 2002). These effects decrease moving from northern Europe to the Mediterranean basin. The Italian climate is becoming warmer and drier due to a reduction in the number of wet days, while precipitation intensity displays a positive trend (Brunetti *et al.* 2004). Among the effects of climatic variability, the modifications of both geomorphic processes and natural hazards, such as those due to landslides, can be included. Many climatic factors are actually considered landslide triggering factors. Rainfall is considered the most common cause of landslides (Crozier 1997) and the most widely used climatic variables are rainfall and temperature (Polemio & Petrucci 2000; Schmidt & Dikau 2004).

The analysis of landslide occurrence due to climatic factors can be carried out using two approaches: 1) spatial analysis and 2) temporal analysis (Polemio & Petrucci 2000). The former can be applied to areas that are widely prone to landsliding, and the latter can be applied to single sites or small areas. In the first case, the area should be homogeneous, while in the second, the studied phenomena should be stationary (Cascini & Versace 1986; Crozier 1986). These conditions define crucial problems in many study cases, as the factors that influence the slope stability often change over time and space. Hence, rainfall-landslide relationships are also likely to change over time, as a result of earthquakes, fires, human activities, and climatic oscillations and trends, or as a result of landslide activity itself. These difficulties should be considered on a case by case basis.

Despite these difficulties, during recent years the attention paid to landslides triggered by rainfall has increased because of their costly effects. The costs of rainfall-triggered landslides are not well documented and often unobtainable. In areas where they do not pose a threat to life, great damage is caused to farmland and communication infrastructures, and pasture bio-mass production is heavily reduced.

Climate change is considered a cause of increasing frequency and magnitude of extreme hydrological events, mainly in terms of increasing intensity and/or duration of extreme rainfall, as happens in Europe (EEA 2004). One of these effects could be an increase in rainfall-triggered landslides.

The relationship between climate and landslides is complex, due to the nonlinear role of the soil-water system (Schmidt & Dikau 2004). Quantitatively assessing the effect of variations of a climatic parameter is often difficult. At the same time, a climatic fluctuation can cause several instability effects in a region, relief or slope, according to the different land use, altitude, slope, vegetation, and type and thickness of soils, for example (Borgatti & Soldati 2002). Research approaches to this complex subject can be distinguished as three types, on the basis of data and methods used: the *palaeo-approach*, the *prediction approach*, and the *historical or time series approach*, as in the case of this paper.

The *palaeo-approach* analyses the effects of climatic conditions that were observed in the past and that do not exist at the present time. In practice, palaeo-landslides are dated and put in relation to climatic conditions that occurred in the Holocene or during the last glacial maximum, aiming to investigate the relationships between past climatic parameters and landslide incidence (Dikau & Schrott 1999; Schmidt & Dikau 2004; Soldati *et al*. 2004).

These studies, some of which were supported by European research programmes, state that some late glacial and Holocene landslides seem to correspond to a climatic variation. Thus, the landslide becomes an indicator of climate change, but the relationship cannot be easily inverted.

The *prediction approach* assesses the effects of future climate conditions. The starting input is generally a downscaled general circulation model that determines the temporal stability variations of slopes using combined slope hydrology/stability models with various levels of complexity (Buma & Dehn 1998; Collison *et al*. 2000; Dehn *et al*. 2000). We note that the results of these predictions are not very often a natural hazard increase: in south-eastern England, the increase in both rainfall and evapotranspiration will leave the frequency of large landslides unchanged (Collison *et al*. 2000), and the displacement rate of a mudslide in northern Italy will decrease (Dehn *et al*. 2000). Schmidt & Dikau (2004) highlight the high uncertainty of climate parameters when the time context is greater than the weather records. Dikau & Schrott (1999) describe difficulties using physically based hydrological and geotechnical slope models and suggest the use of simpler tank models. Each of the abovementioned authors underlines difficulties or uncertainties that require further efforts and knowledge.

The *historical approach* is based on landslide observations and monitored climatic data, using physical or statistical methods of analysis. In this case, the frequency, intensity, magnitude, and/or duration of rainfall are taken into account, emphasising changing climatic conditions (Crozier 1997). Due to the starting date of gauge networks, this approach can be applied from the nineteenth century (with country or regional differences) to the present. Even though this approach permits a trend analysis (Petrucci *et al.* 2008), which is considered a fundamental prerequisite to evaluating changes in landslide activity both in Europe (Dikau & Schrott 1999) and worldwide, scientific study cases are not frequent. The reason for this could be the lack of historical data on landslides and/or difficulties in collecting data (Dikau & Schrott 1999).

Schmidt & Dikau (2004) tried to reduce these difficulties by extrapolating seasonal rainfall and temperature time series of the last 500 years using proxy data. These data are then compared to landslide occurrence on selected hill slopes, using GIS and numerical modelling to calculate groundwater fluctuations.

The present article defines a methodology and a study case based entirely on time series of rainfall, temperature and landslide occurrence.

Methodological approach

A method based on the comparative analysis of two databases is proposed: a landslide database and a climatic one. In practice, landslides occurred in a wide period and the climate data characterising the same period are cross-checked in order to assess the effects, if any, of a climatic trend on landslide activity.

In the following, the characteristics of the two databases are briefly described, underlining the difficulties and assumptions that must be made in order to perform the analysis. Finally, the steps of comparative analysis for these two kinds of data are outlined.

The landslide database: data and elaborations

Historical research can be a useful tool to obtain the series of landslide events that affected a study area over a long period. Many authors (Flageollet *et al*. 1999; Guzzetti 2000; Glade 2001; Barnikel & Becht 2003; Glaser & Stangl 2003, 2004) have shown the usefulness of historical data in the study of past events. According to Carrara *et al*. (2003), despite the lack of consensus on the reliability and usefulness of historical information, some investigators have used these records for single landslides or landslide-prone regions (Wieczorek & Jäger 1996; Ibsen & Brunsden 1996; Cruden 1997; Glade 2001; Calcaterra *et al*. 2003), obtaining results that are useful in landslide hazard assessment.

In the following, the main steps for creating the landslide database are listed.

Data gathering. The first problem is data collection. Some interesting cases of landslide databases are available on the web at a nationwide scale, for instance for Australia from 1842 to today (Australian Government 2009) and for Nicaragua before 1990 (Devoli *et al*. 2007).

In other cases, data concerning more than one type of natural phenomenon are collected, as in the database of the Australian Risk Frontiers, which concerns earthquakes, landslides and tsunamis that occurred between 1900 and 1998 (Blong 2004), or the Italian database AVI, which concerns landslides and floods that occurred in Italy in the past centuries (Guzzetti *et al*. 1994). A review of the content and accessibility of selected groups of event-specific disaster loss databases at different scales (international, national or regional) can be found in Tschoegl *et al*. (2006). Unfortunately, such databases are rare: in several countries, no single agency is assigned the task of systematically collecting landslide data, although different amounts of data sources, varying from country to country, are available.

More generally, in order to collect necessary data, two steps must be taken: 1) identify available national/regional databases containing data on landslides; and 2) in depth historical analysis, gather the entire dataset in the case when no databases are available, or in order to fill gaps if available databases are characterised by a low spatial/temporal resolution. There is a large number and variety of documents in which historical data may appear sporadically or systematically (Ibsen and Brunsden 1996; Llasat *et al*. 2006). Documents must be carefully analysed in order to correctly understand and extract data on landslides.

Data digitisation. Once the data have been gathered, the acquisition process requires an effort that strictly depends on the type of document containing the data. Newspaper articles can be acquired quite rapidly using a digital camera or a photocopier and transcribed. Often, their low quality does not allow for an automatic conversion of image files to text files. The same is true for scientific and technical articles or, generally, for other typewritten documents.

On the other hand, reimbursement requests or, more generally, documents gathered in historical archives and concerning the period antecedent to ‘50s, are mainly handwritten. In these cases, long and patient work is necessary to understand the writing and transcribe the crucial parts.

At the end of this step, all of the gathered documents are converted into text files to be entered into the database.

Data validation. One factor to take into account is the reliability of documents from which data have been collected. In general, the reliability is affected by bias mainly when the document is a refund request and/or the author is not an expert on landslides. The reliability classification of documents presented in this work is usually general, but can be easily adapted to local peculiarities.
In this classification, reliability can be defined using sub-ranges, 0 to 1, 1 to 2, 2 to 3, and 3 to 4, according to the type of document and the skill of the author. The highest reliability sub-range, 3 to 4, is used to characterise either scientific publications or governmental texts on the arrangement of both first aid measures and long-term support for people living in affected areas (i.e., daily allowance and temporary tax cuts for evacuated people). Scientific articles represent a very low percentage of data sources, because they generally concern single landslide phenomena or phenomena affecting selected territorial sectors, and they very often do not report the series of landslide/s activations but rather the conditions at the moment when the article was written.
Reliability 2 to 3 is the sub-range for reports by technicians of departments in charge of damage repair and refunding. In general, these technicians are engineers who assess the on-site type and/or cost of remedial measures. Because they are trained and do not have any personal interest in the distribution of refunds, their reports can be considered fairly reliable.
Reliability 1 to 2 is the sub-range typically used for reports of local technicians, as is the case for refund request reports written by local authorities or damaged owners. This low reliability takes into account the fact that the appraisal of damage can be stressed to increase the attention of the governmental agency or insurance companies.
Reliability 0 to 1 classifies data obtained from historical books and newspapers. In these cases, both the skill and individual experience of the document's author must to be taken into account. Both reporters and historians are not expert in landslides, so they tend to emphasise the damage.

However, as previously mentioned, newspaper articles are characterised by a continuity in time that makes them a good source to avoid gaps in the data series.

During the data validation step, the gaps must be taken into account that could affect the oldest periods of the series, characterised by a minor number of information sources and, more generally, by a minor facility in the diffusion of information, also concerning landslides. This problem does not exist for the most recent parts of the series, also characterised by a greater understanding and concern about environmental problems. For these reasons, it must to be taken into account that an underestimation of the number of landslides can affect the oldest periods, and an overestimation can occur for the most recent years.

In the data validation phase, the database must be carefully checked in order to avoid data duplications. Especially main landslide phenomena can be quoted by several data sources. These phenomena are often reported by more than one newspaper edition.

Limitations of the historical databases on landslides. Regardless of the type of source from which data are gathered, some restrictions must be taken into account:

1. Research can never be considered complete, because accidental factors can cause document losses;
2. Damage is often considered in reference to municipalities, so administrative boundaries have to be taken into account;
3. Phenomena that occurred in unpopulated areas and did not induce damage can be unrecorded because most available sources (except for technical and scientific articles) are more related to the effects (damage) than the phenomenon itself;
4. Uncertainty can also affect the date of the landslide events. Especially in reimbursement requests filled after heavy rainfall triggered landslides over wide areas, applications were often performed using prescribed forms, in which events are indicated by the year of occurrence (i.e., landslide event of 1951). Thus, the requests depict the final result of the event, and not the exact days during which

damage occurred. In these cases, by analysing all of the data concerning the period in which landslides were triggered, a period restricted to some days can generally be identified and, despite an uncertainty margin, the dates of the phenomena can be assigned.

Database organisation. The gathered data are organised as database records. Previous standard methodologies to elaborate historical data are not available. This is because it deals with non-instrumental data, that is, text descriptions from which phenomena (landslide) and effects (damage) must be inferred and converted into qualitative or semi-quantitative values.

Each text file should be transformed into a database record for which the date of the landslide event, the municipality in which it occurred, and the details about triggered phenomenon are described.

In general, the name of the municipality where damage occurred is quoted in almost all the data, but place names of areas hit are often not pinpointed. Even if a place name is available, the area really affected cannot be delimited, because the author of the document does not supply precise information on the perimeter of the area hit by the phenomenon (unless the document is a scientific article).

Therefore, the basic cell in which the study area can be discretised is generally the municipality boundary. To be strict, the data allow to identify the occurrence/non-occurrence of a landslide only in a municipal cell. Taking into account the temporary effects of some kinds of phenomena, only detailed surveys carried out immediately after the event can supply a reliable delimitation of hit areas. A municipal cell is also proposed because it can be almost congruent with the Thiessen polygons defined on the basis of gauges of the climatic monitoring network.

The organisation of such a database can have several kinds of uses in the study of landslide processes. Moreover, for the present work, an index must be assessed. After characterising the entire dataset, in order to characterise the seasonal recurrence and the spatial pattern of landslide data the *monthly landslide number* ML must be evaluated, as the total number of landslide occurrences in each month.

The climate database: data, elaborations and cross-analysis with the landslide database

The assessment of the effects of climate variability on the trend of landslide occurrence should be based on time series of monthly rainfall, number of wet days and temperature data. These data are freely available worldwide, with differences in length, density and accuracy.

Time series should be tested for homogeneity using the Craddock test or other procedures (Craddock 1979), and inhomogeneous data should be discarded. The time series or gauge location and number should be selected to obtain the maximum or, at least, a sufficient gauge density and spatial continuity, mainly of rainfall and secondly of temperature, covering the largest monitoring period with the lowest number of data gaps.

A day with precipitation greater or equal to 1 mm is defined as a *wet day*. If time series of *monthly number of wet days* (hereafter *D* or *wet days*) are unpublished, rainfall or *precipitation* (*P*) time series, on a daily basis, should be used to obtain D. On this basis, the *precipitation intensity*, hereafter *I*, can be calculated as the average rain amount per wet day.

The effect of variability of the *temperature* (*T*) on hydrological processes affecting landslides increases moving from humid to arid climates and changes from season to season.

The P, D, I, and T regimes can be compared to the landslide regime, as defined below.

In order to assess the precipitation variability in the region, the *monthly precipitation index* $IP_1(x,y)$ can be calculated for each month, where x indicates the month (x=1, 2, …, and 12, starting from the first month of the hydrological year) and y the year (starting from the beginning of the monitoring period):

$$IP_1(x,y) = \frac{\sum_{i=1}^{n} MP_i(x,y)}{\sum_{i=1}^{n} AMP_i(x)} 100 - 100 \qquad [1]$$

where MP_i is the Monthly Precipitation at gauge i of the month (x,y) and AMP_i is the Average Monthly Precipitation of month (x) at gauge i, with i=1, 2, …, n, where *n* is the number of available gauges in the month (x,y).

In a similar way, the monthly, bi-monthly, tri-monthly, and … m-monthly indices IP_1(x,y), IP_2(x,y), …, IP_m(x,y), with m=1, 2, …, 12, can be defined [2]:

$$IP_m(x,y) = \frac{\sum_{j=z-m}^{z}\sum_{i=1}^{n} MP_{i,j}(x,y)}{\sum_{j=z-m}^{z}\sum_{i=1}^{n} AMP_{i,j}(x)} 100 - 100 \qquad [2]$$

In expression [2], z represents the position number of months, in progressive order, starting from the first month of the first hydrological year. IP_m(x,y) considers rainfall values observed in month z and in the m-1 previous months, where m is the duration of the considered index. Using this dimensionless index, a unique precipitation time series can be applied to the whole region.

Defined on a basic monthly duration, the index duration should extend up to 12 months at least.

IP_{12}(12,y) considers rainfall values observed in the whole hydrological year y, so it can be defined *IP(y)*, the *yearly precipitation index* of year y.

As IP_m(x,y) is defined, the relevance of gaps in some time series is low and can be neglected if the number of incomplete time series is low during some months. As MP_i(x,y) is positive or equal to zero, the IP_m(x,y) minimum value ranges from a theoretical -100, due to no rainfall at each of the available n gauges in the considered m-month period, to an undefined positive value, up to values due to exceptional rainfall observed during the considered m months. Negative values indicate precipitation less than the average in the whole area, while positive values indicate the contrary. The range should be narrower as m increases; this effect is due to the minimum increase and mainly the maximum decrease of IP_m(x,y).

Similar indices IT_m(x,y), ID_m(x,y), and II_m(x,y) can be defined for parameters T, D, and I.

The range and variability interpretation of ID_m(x,y) and II_m(x,y) should be similar to those of IP_m(x,y). As the monthly temperature can be negative and the variability is different and lower than the monthly rainfall parameters, the IT_m(x,y) range should be the narrowest and almost symmetrical with respect to zero, whatever m value is considered.

If ML(x,y) is the *monthly landslide number* recorded during the month x,y, then IL_m(x,y), the m-monthly index of landslide occurrence, is:

$$IL_m(x,y) = \frac{\sum_{j=z-m}^{z}\sum_{i=1}^{n} ML_{i,j}(x,y)}{\sum_{j=z-m}^{z}\sum_{i=1}^{n} AML_{i,j}(x)} 100 - 100 \qquad [3]$$

where AML_i is the *Average Monthly number of Landslides* of month x in cell i, with i=1, 2, …, n, where n is the number of cells into which the study area or region is divided. The total AML_i (x), for i=1, 2, …, n, defined for each month, defines the landslide regime.

The range and variability interpretation of IL_m(x,y) should be similar to those of IP_m(x,y), and the range should be much wider due to the effect of peak values of each time series.

The five groups of indices (IL, IP, IT, ID, and II) permit a comparison of time landslide variability to climate variability, considering durations from one month to a whole hydrological year.

As these constitute time series, trend analysis and cross-correlation analysis should be the basic methods for the time series analysis (Brockwell & Davis 1987).

The Calabria case study

Calabria, the southern-most Italian region (Figure 1), is a peninsula with a surface of 15 230 km^2, a perimeter of 738 km, and mean and maximum altitudes of 418 and 2266 m a.s.l. (Above Sea Level), respectively. Almost 90% of the regional territory shows topographic relief and 10% is represented by coastal and fluvial plains; 93.5% of the region is lower than 1300 m a.s.l. From an administrative point of view, the region is divided into five provinces, and 409 municipalities. The population density (133 inh/km^2) is lower than the national value (198 inh/km^2) (ISTAT 2003).

The region is made up of a stack of allochthonous terrains (from Palaeozoic to Jurassic), composed of crystalline rocks, mainly gneiss and granite, derived from both continental and oceanic crust, stacked, during the middle Miocene (Tortorici 1982), over the carbonate units of northern Calabria (Ogniben 1973). During the emplacement of terrains and onwards, the Neogene's tectonic melange and flysch built a substratum that underwent extension because of uplift that started in Quaternary and is still active.

The LAND-Cal database

Several data concerning landslides that occurred in Calabria in the period 1921-2006 have been obtained from ASICal (2009), a database of landslides and floods that occurred in this region during the past centuries. In order to fill some space/time gaps in the series, historical studies were carried out.

In this way, a new database, named LAND-Cal and containing the landslides that occurred in Calabria between 1921 and 2006, has been created. Depending on the type of historical documents from which data were collected (mostly reimbursements requests and newspaper articles), LAND-Cal concerns mainly landslides that caused damage. For this reason, LAND-Cal data concerning damaging landslides are sufficiently reliable. However, there may be gaps related to landslides that did not cause damage.

LAND-Cal data have been sorted chronologically and by municipality. Each record of the database, generally obtained from a single historical document, corresponds to a *landslide event* affecting a certain municipality on a certain date. It has been used the term landslide event because, in a selected municipality, more than one phenomenon can occur during or after heavy rainfall.

The available data, collected by hydrological years (from September 1 to August 31), have been conventionally named as the solar year, which includes September.

LAND-Cal contains 2982 records of landslides that occurred in the analysed 85 years If the descriptions are adequately detailed (the case for 39% of records), landslides have been conventionally classified, based on the maximum depth of failure (Md) as shallow (Md<10 m) or intermediate- and deep-seated (Md>10 m) (Hutchinsons 1995). Thus, 781 cases (26%) are included in the first group and 374 cases (13%) are classified in the second.

The mean number of landslide data per year is 35 (Table 1). The maximum value of landslide events pertain to the hydrological year 1953 (195 cases, 54%).

Analysing Figure 2, it can be noticed that most of the municipalities have been affected by between 1 and 10 landslide events. The peaks with more than 30 events represent some densely populated municipalities located both near the coasts and in the central-western sector of the region (Petrucci & Pasqua 2008).

Each year of the study period shows at least one event, and only five years show the minimum value (1 case; 1922, 1924, 1931, 1943, and 1961). For the first four years, the low number of data may be related to a data gap, also taking into account the low data availability in Calabria before the 1950's (the period in which regional newspapers appeared).

By dividing the study period into decades, the decade 1950-1959 records the highest number of cases (699 cases, 23%): in this period, three particularly dramatic damaging hydrogeological events affected Calabria (Petrucci *et al*. 2008). The minimum value was obtained for the decade 1920-1929 (125 cases, 4%). A high total number of cases characterises the periods 2000-2006 (419 cases, 14%, in a 6-year period) and 1930-1939 (389 data, 13%). The mean value of data per decade is 320 cases if the period 2000-2006 is excluded. For the whole study period, the maximum number of data per municipality has an average of 10, but assessed by decade, it ranges from 5 for the first analysed decade, to 20 for the period 2000-2006.

Dividing the study period in intervals of five years, the maximum value of landslides pertains to the periods 2000-2004 (401 cases, 13%), 1955-1959 (381 cases, 12%) and 1950-1954 (318 cases, 10%).

November is the month characterised by the highest number of data (21%), followed by January (14%) and February (14%) (Figure 3). More generally, 67% of data are recorded between November and February. July is characterised by the lowest value (21 cases, 0.7%).

Figure 4 indentifies the areas characterised by the highest landslide density and frequency. The north-west sector has been highly affected by landslides, although of different intensities, throughout the analysed sub-periods. Particularly in the decades 1950-1959 and 1980-1989, the number of data per municipality shows some peaks with more than 6 landslide events per municipality. The eastern side of the region, on the other hand, shows more than a decade characterised by a low number of municipalities hit (1920-1929, 1940-1949, and 1960-1969), and, more in general, the number of data per municipality per decade is lower than 6. The southernmost sector of the region was affected by landslide events during each decade, also with peaks characterising some densely populated municipalities located along the Tyrrhenian coast.

The CLIMATE-CAL database

The climatic database was built starting from a climatic database created to study climate change in southern Italy and based on monthly time series of rainfall and temperature since 1821 (Polemio & Casarano 2008).

Several time series and some parameters were added to improve the spatial density of the time series, taking into account the purpose of the cross-analysis with landslides. Thus, a new database, named CLIMATE-Cal and containing monthly data of 263 Calabria gauges, was created. Removing inhomogeneous data, 65 gauges were selected to provide good elevation coverage of the study area (between 3 and 1300 m a.s.l.). In this way, both a sufficient gauge density and spatial continuity, mainly of rainfall and secondly of temperature, covering the largest monitoring period with a minimum of data gaps (Figure 5) can be obtained. Among the selected gauges, forty-five (located at altitudes between 5 and 1300 m a.s.l.) are also equipped for temperature measurement. Published data cover the period from 1916 to 2006 (monthly temperature data are available only since 1924), including wet days data (Calabria Region). Some data for this period are unpublished (such as during the Second World War) and were made available thanks to the Calabria Civil Protection. A generalised failure of the whole regional temperature monitoring network was registered for 18 months during the period 1975 to 1982.

The climate in Calabria is typically Mediterranean, characterised by hot and dry summers and long wet periods in the autumn and winter, sometimes lasting until the early spring (Figure 3). The mean annual precipitation ranges from 503 to 1778 mm (1172 mm as the regional spatial mean). The spatial variability is mainly due to the altitude effect (Figures 1 and 4) and secondly to the distance from the western coast (at same altitude the precipitation is higher on the regional western side), as the main perturbations generally move from west to east (Petrucci & Polemio 2009). The annual mean for D ranges from 54 to 118 mm (93 as regional mean), for I ranges from 7.3 to 13.8 mm/day (11.1 mm/day as regional mean), and for T ranges from 8.9 to 18.7 °C (16.0°C as regional mean). The spatial variability of these variables is mainly correlated to the altitude.

The P regime in the region is almost homogeneous. Rainfall starts to increase from September up to the monthly maximum of December and then decreases; minimum rainfall is recorded in July (Figure 3). Similar trends are observed for D and I, for which the maximum is observed in November. On the other hand, T decreases from September to the minimum of January, and then increases up to the August peak.

The yearly index ranges of P, D, and I are similar (Table 1), while that of T is narrower. The range of IL is an order of magnitude wider, due to the frequent occurrence of both one-landslide years and years with hundreds of landslides. Figure 6 shows the yearly time series of all analysed indices and their linear trends.

The IL trend is positive (the angular coefficient of the trend straight line, a_{IL}, is 0.689). A polynomial trend line of second order highlights two different trends. From 1920 to 1952, the trend is increasing; thereafter, the slope progressively decreases until 2005. In this second period, IL is substantially steady. The IP trend decreases throughout the period (a_{IP} is -0.28). This figure is perfectly coherent with the results of climate change analysis for all of southern Italy (Polemio & Casarano 2008). This research highlights a widespread decreasing trend of annual precipitation in southern Italy, and for Calabria, a decrease equal to 22% of mean yearly precipitation affecting the last 80 years. The ID and II trends are decreasing (a_{ID} and a_{II} are -0.06 and -0.24, respectively). The ID trend is typical for whole country, as highlighted by Brunetti *et al.* (2004). The same authors determined an increasing trend of II for northern Italy but not for southern Italy, for which they did not find a significant trend, probably due to low density of analysed gauges (only one gauge in Calabria). The IT trend is slightly decreasing (a_{IT} is -0.04). In this case too, a polynomial trend line of second order highlights two different trends. From 1924 to 1980, the trend is less decreasing, while ever since, the slope is progressively increasing, up to 2005, like for southern Italy (Polemio & Casarano 2008).

The time series of the indices IL_m, IP_m, ID_m, II_m, and IT_m were calculated for m=1, 2, 3, 6 and 12. For the sake of brevity, some statistical values of these time series are summarised in Table 2, for m equal to 1 and 3; further details are highlighted in the paragraph of cross-analysis and discussion.

The complete understanding of landslide number trend should be pursued considering the anthropogenic role. The attention should be focused on the increase of population number and needs, deforestation, tillage, increasing cultivation and careless urban enlargement into natural hazard prone areas, as observed for some areas of Calabria and southern Italy (Petrucci & Polemio 2007; Polemio in press).

Cross-analysis and discussion

The regime of the analysed variables shows a good correlation between the monthly landslide number and the selected variables (Figure 3). P, D and I reach peaks between December and January, like L. In statistical terms, it is useful to determine the cross-correlation coefficient CC^l of the variable lag l=1, 2, … . CC^0 is equal to 0.93, 0.87 and 0.86 for P, D and I, respectively. The correlation with T is slightly weaker and, as is reasonable, negative (CCT=-0.77). For each variable, CC decreases as l increases, and becomes statistically not significant for l>3. Thus, in terms of the mean hydrological year, the variability of the landslide number is mainly described by precipitation, and progressively less by wet days, precipitation intensity and temperature.

Moving from mean monthly values to the yearly time series, these results are confirmed (Table 3). In this case, the results are statistically identical either if L, defined as the yearly total number of landslides in each cell of the region, or IL, is considered. CC^0 decreases from 0.46 to 0.19 moving from IP to II. The correlation with IT is null and statistically not significant. For each variable, CC decreases as l increases. IP is highly correlated with ID and II; this result should be considered if a forecasting model for L is defined using IP, ID, and II as independent variables.

In any case, the L or IL trend (Figure 6), both linear and polynomial, cannot be justified considering the trends of IP, ID, II and IT. In fact, the effect of decreasing precipitation, wet days, precipitation intensity (the role of II could be questioned as the intensity amount should be compared to the infiltration capacity of the soils) and the recent increase in temperature (self-evident in the case of the polynomial trend) should not cause an increase of landslides in an area with a semi-arid and temperate climate.

The analysis of yearly time series was repeated calculating the moving averages for 2, 3, 5, and 10 years of each parameter. The obtained results are quite similar, and the correlation coefficients decrease as the number of years increases. This happens for each index, with the exception of ID, the coefficient of which remains almost steady.

On a ten-year basis, the mean number of landslides per decade is 320, if the period 2000-2006 is excluded (Figure 4); a high total number of cases characterises the period 2000-2006 (419 cases, 14%, in a 6-year period). The minimum landslide number observed in the twenties (125 cases, 4%) could be related to both ordinary precipitation and very few wet days (the 10-year moving average defines the minimum value of ID in 1929). The peak landslide number observed in the thirties (389 data, 13%) seems justifiable in terms of both high precipitation and number of wet days (the 10-year moving average defines the maximum value of IP in this decade).

It is possible to determine CC^l for the monthly time series of L with the monthly time series of each index with a variable m value. The peak CC^l of each couple of time series is shown in Table 4. The peak is observed for l=0, except for ID_2 (l=4), ID_3 (l=4), and for each IT time series. It should be considered that the correlation with temperature is statistically not significant, while CC^l shows a very low variability for l≤4 in the case of the ID_2 and ID_3 time series. The peak CC^l decreases as m increases, apart from the negligible case of ID, in which it slightly increases. As a result, in terms of monthly variability, the highest linear relationship of $IL_m(x,y)$ for month x',y' with $IP_m(x,y)$, $ID_m(x,y)$, or $II_m(x,y)$, is, in practical terms, almost equal to that observed for m=1 for each time series for the same month x',y' or for l=0. On this basis, the landslide number should be simply and roughly forecasted using the monthly values of precipitation, wet days and precipitation intensity.

Conclusions

A method to characterise the statistical relationship between landslide occurrence and monitored climatic parameters has been defined and tested on an extensive Italian region.

The method allows simplifying the problem of the comparative analysis of several time series of different data types by defining some simple indices. These indices simplify the study of the considered phenomena, which show significant spatial and temporal variability, to a case of time series analysis. At the same time, the relevance of climatic data gaps and lack of homogeneity are removed.

For the case study of the Calabria region (Italy), the analysis indicates that, despite the favourable trend of climatic parameters, landslide occurrence is not decreasing. This is due to the effect of two combined factors.

The first is a slight underestimation of the number of landslide occurrences in the oldest part of the series, due to a lack of concern about environmental problems and of diffusion of information by means of local newspapers.

The second factor is a sort of amplification of rainfall effects on slopes, in terms of damage resulting from landslide activation. In the most recent decades, the increasing density of vulnerable elements (urban settlements, road networks and so on) in landslide-prone areas has lowered the damage threshold. In practice, in order to overexploit some specific sectors, man-made modifications of the landscape (i.e., cuts for roads) have changed the equilibrium conditions of slopes. On the other hand, because of the presence of vulnerable elements, each landslide that occurs in these densely populated municipalities is well known and reported by the media, because it almost certainly induces damage.

The analysis of the monthly time series highlights the main role of precipitation, wet days and intensity observed within a month before each considered event.

The role of temperature seems, as a whole, negligible. This result could be due to the linear type of analysis carried out, which could underestimate the relevance of this parameter in the considered climatic conditions.

More efforts will be necessary to take into account the effect of temperature in terms of evapotranspiration and net rainfall, and to move towards a daily approach of time series analysis. In addition, deeper investigation should be pursued to refine the analysis using regionalisation criteria.

The assessment of the anthropogenic role on the trend number of landslide is a very complex subject that should be deeply discussed in further researches.

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FIGURE CAPTIONS

Fig. 1. Calabria region maps. (a) 300 m a.s.l. contour line and peak altitudes. (b) Simplified geological sketch of the region: (1) Limestone and dolostone; (2) metamorphic and igneous rocks; (3) clays, marls, and evaporitic rocks; (4) sandstones, marly clays, and limestone marls; (5) flysch and clayey formations; (6) conglomerates, sands, and sandstones; (7) alluvial deposits.

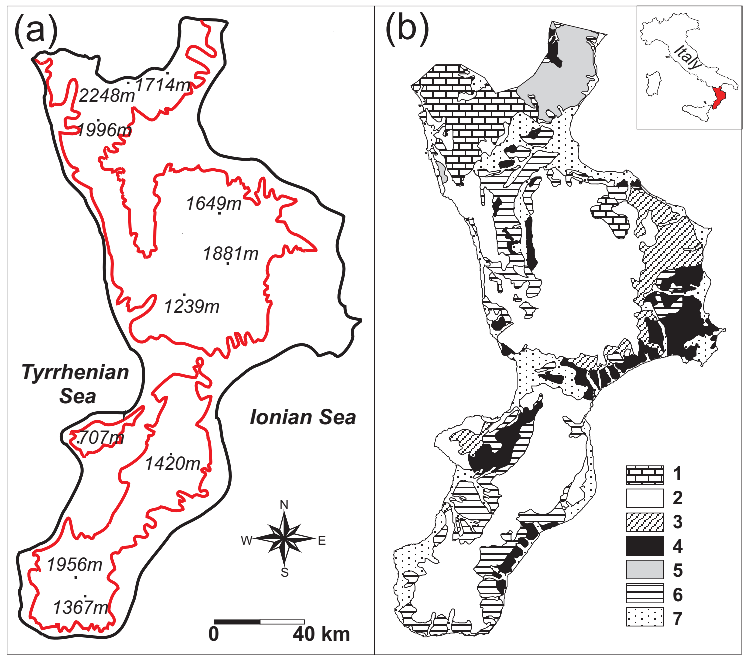
Fig. 2. Municipalities of Calabria classified according to the total number of landslide events occurred during the study period (1921-2006), as in the legend.

Fig. 3. Regime of precipitation (P), landslides (L), wet days (D), precipitation intensity (I), and temperature (T).

Fig. 4. Municipalities of Calabria classified according to the number of landslide data recorded in the decades of the study period. (a) 1921-1929; (b) 1930-1939; (c) 1940-1949; (d) 1950-1959; (e) 1960-1969; (f) 1970-1979; (g) 1980-1989; (h) 1990-1999; (i) 2000-2006.

Fig. 5. Map of selected gauges (dots) and of contour lines of mean annual values of precipitation (A, mm), wet days (B), precipitation intensity (C, mm/day), and temperature (D, °C).

Fig. 6 Linear trend and time series of yearly indices of landslides (L),precipitation (IP), wet days (D), precipitation intensity (II), and temperature (IT). The linear trend is a gray line in each diagram; a polynomial trend line is added for L and IT with a black line.



(a)
2248m
1714m
1996m
1649m
1881m
1239m
Tyrrhenian Sea
Ionian Sea
707m
1420m
1956m
1367m
N
W
E
S
0
40 km
(b)
Italy
1
2
3
4
5
6
7

Figure 1

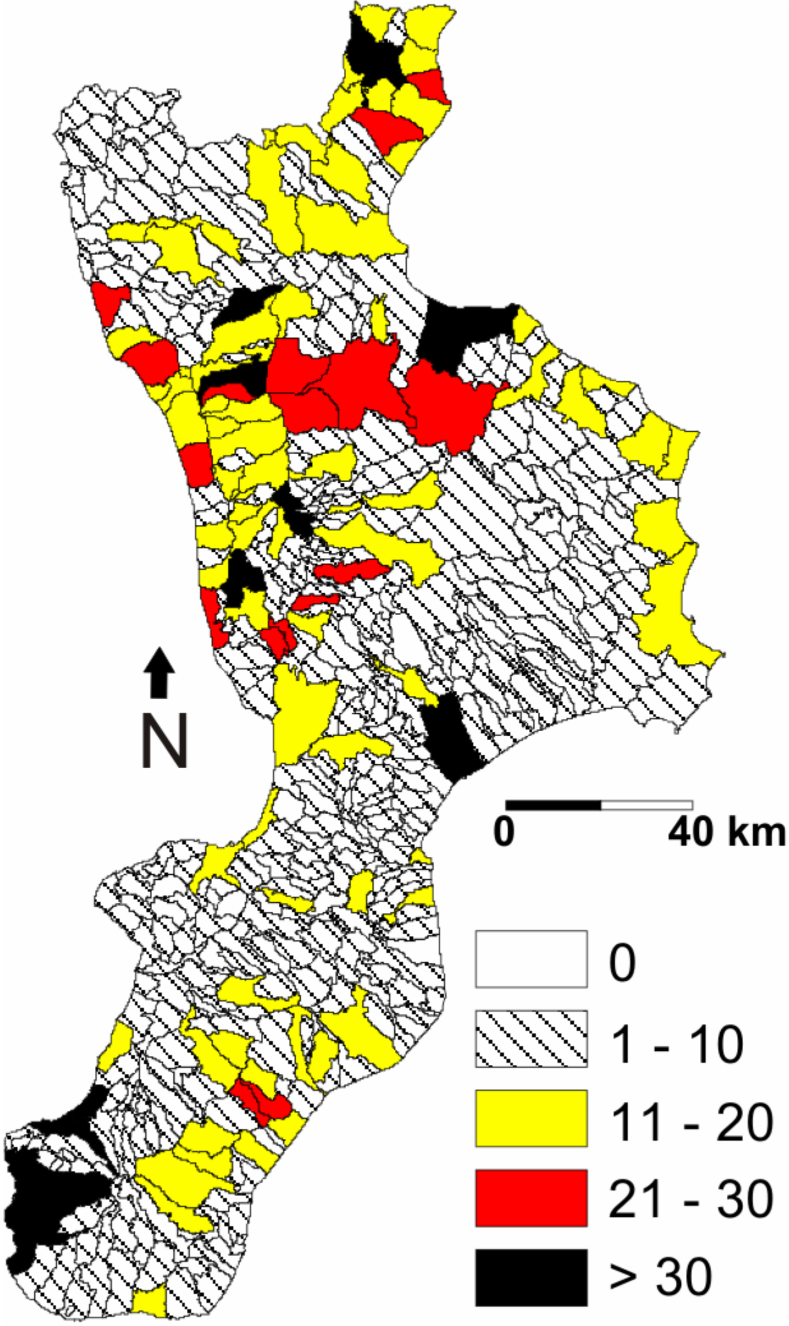
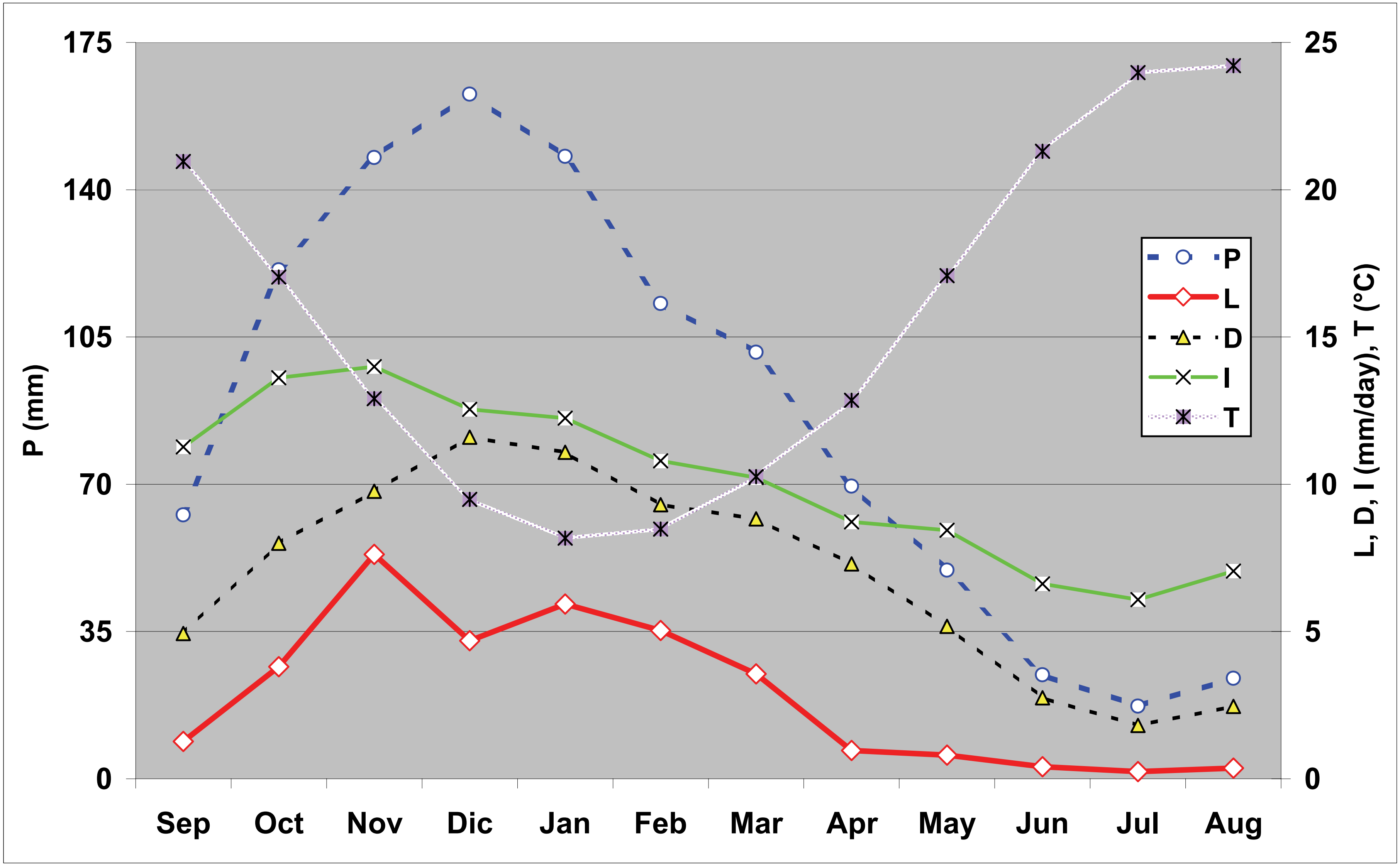


Figure 2


175
140
105
70
35
0
P (mm)
25
20
15
10
5
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L, D, I (mm/day), T (°C)
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Figure 3

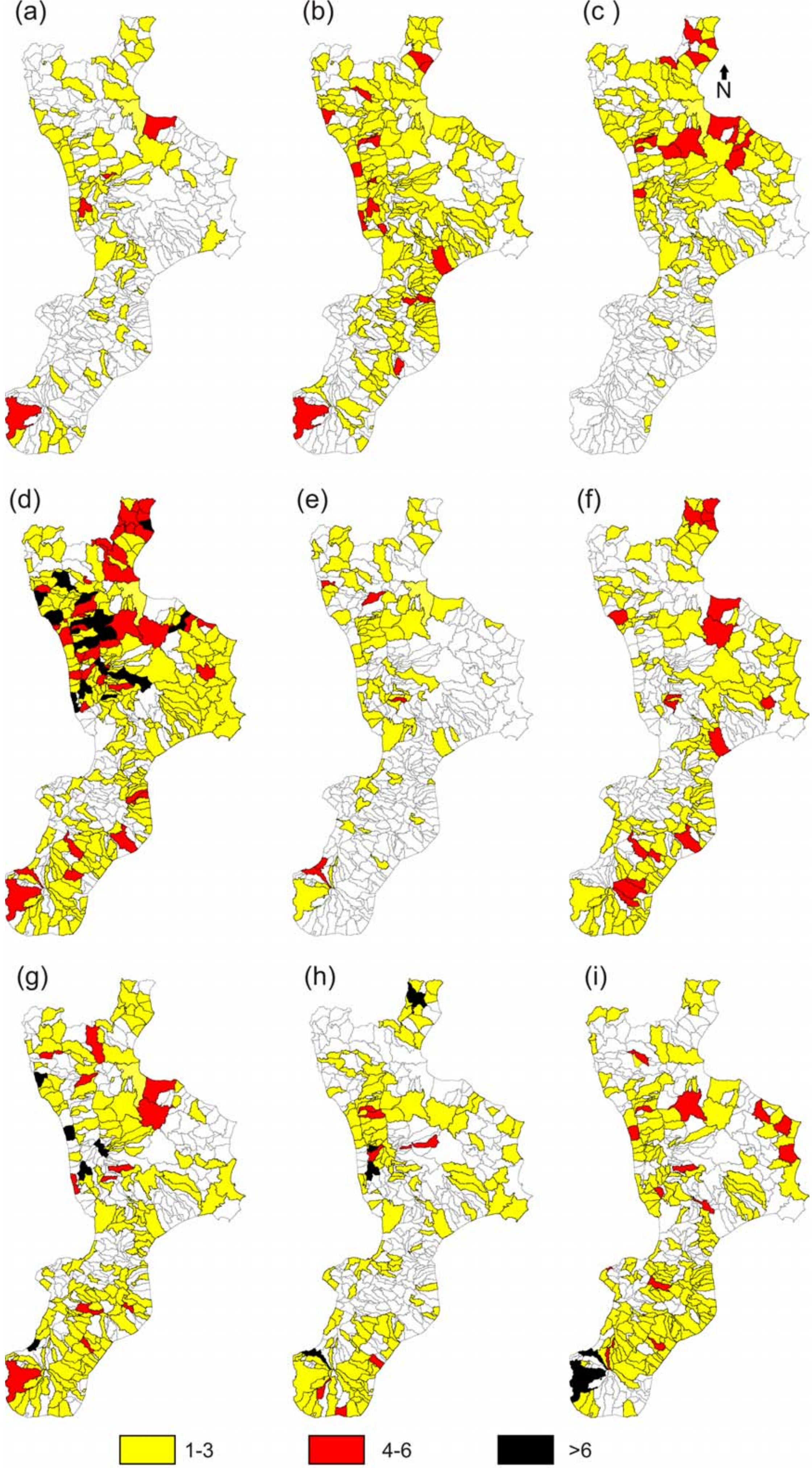
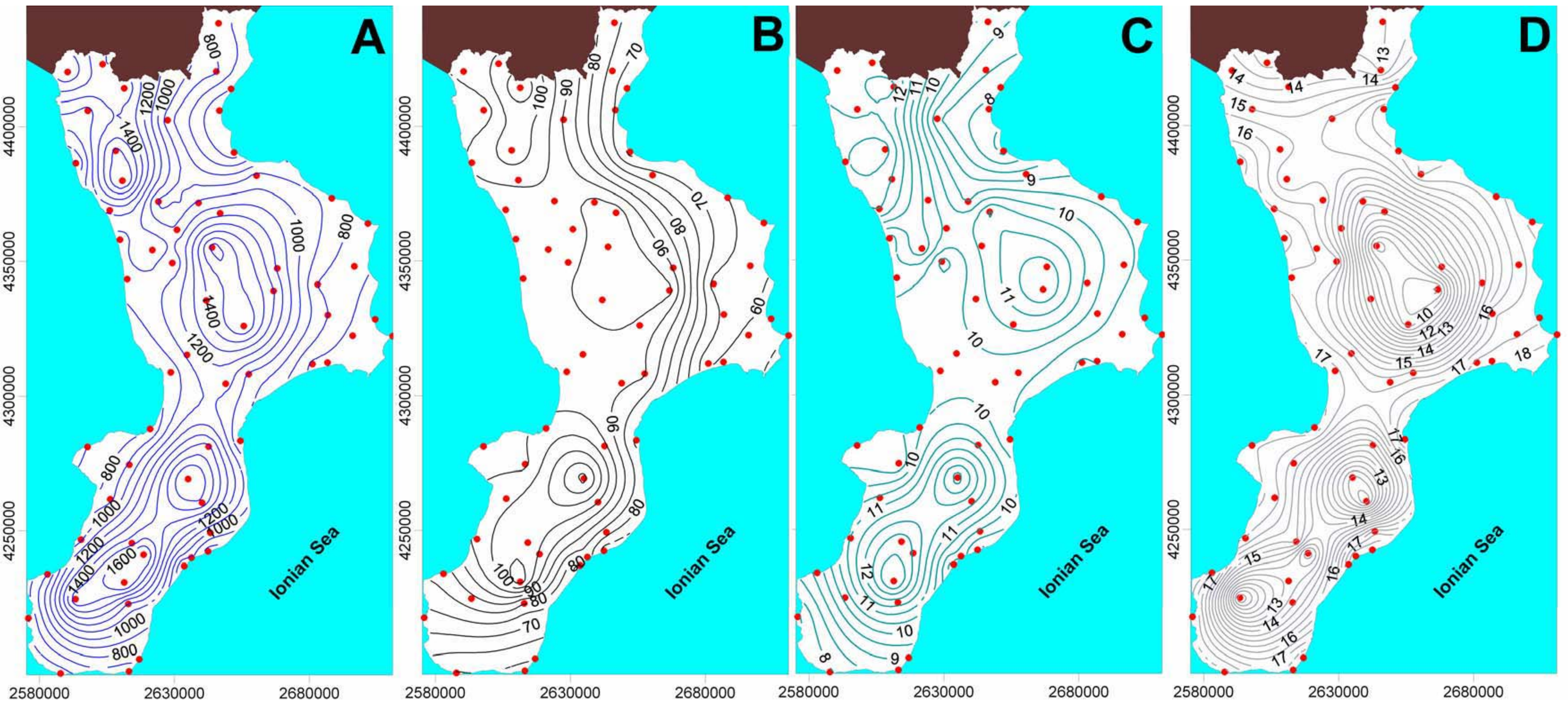


Figure 4


A
B
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4400000
4350000
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2580000
2630000
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Figure 5

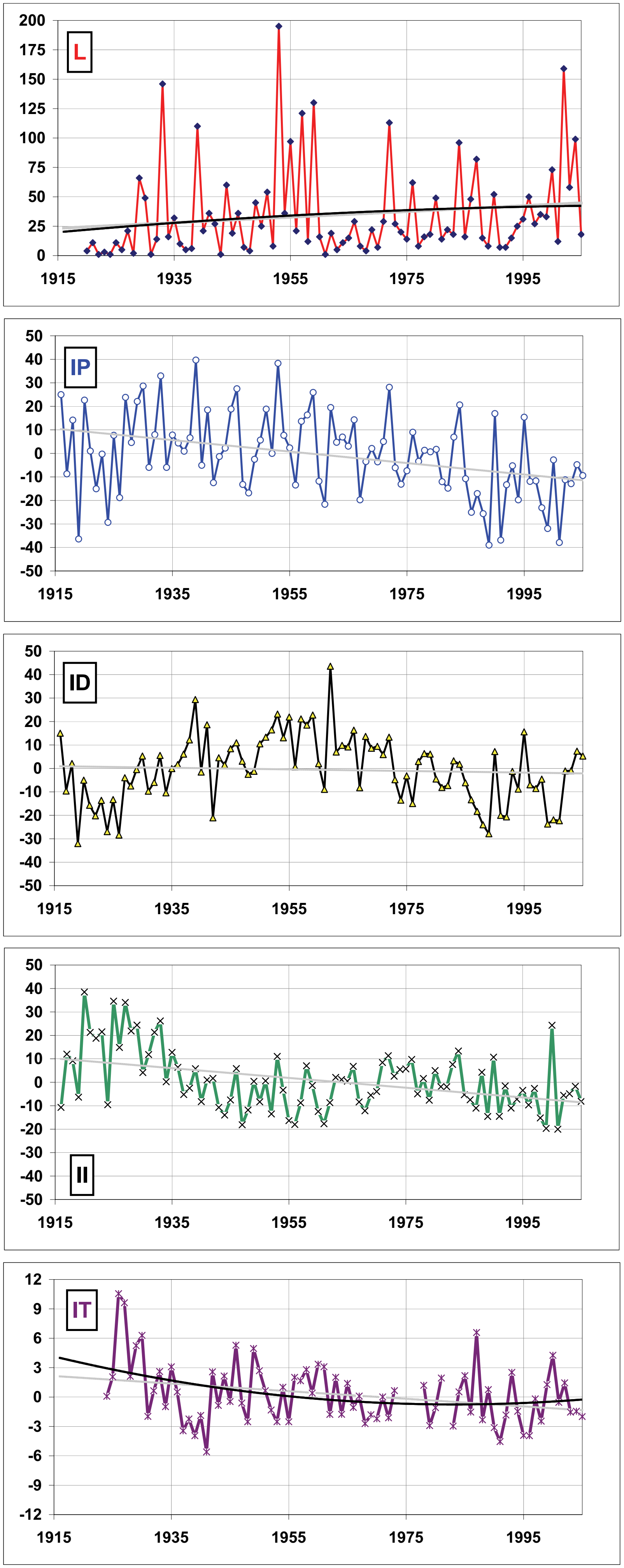

Figure 6

Table 1 *Statistics of yearly time series of landslides (L) and of indices of landslides (IL), of precipitation (IP), of wet days (ID), of precipitation intensity (II), and of temperature (IT)*

	L	IL	IP	ID	II	IT
Minimum	1	-97	-39	-32	-20	-6
Mean	35	0	-1	-1	1	0
Maximum	195	462	40	44	39	11
Min. year	many	many	1989	1919	2001	1941
Max. year	1953	1953	1939	1962	1920	1926

Table 2 *Statistics of monthly time series of landslides (L) and of indices of landslides (IL), of precipitation (IP), of wet days (ID), of precipitation intensity (II), and of temperature (IT). m) One month time series, 3m) 3-month time series (as total in the case of L)*

	L		IL		IP		ID		II		IT	
	m	3m	m	3m	m	3m	m	3m	m	3m	m	3m
Minimum	0	0	-100	-100	-99	87	-99	-84	-100	-71	-36	-25
Mean	3	9	0	1	-1	-1	0	-1	0	1	0	0
Maximum	94	138	4003	2731	296	166	291	156	259	126	34	19
Min. date	many	many	many	many	6/28	8/31	8/60	8/31	7/39	9/46	12/91	2/29
Max. date	1/03	1/34	9/00	9/00	9/00	9/55	8/95	9/55	9/00	10/21	3/26	4/26

Tab. 3 *Cross-correlation coefficient (lag =0) of yearly time series of landslides (L) and of indices of landslides (IL), of precipitation (IP), of wet days (ID), of precipitation intensity (II), and of temperature (IT)*

	L	IL	IP	ID	II	IT
L	1					
IL	1	1				
IP	0.46	0.46	1			
ID	0.33	0.33	0.75	1		
II	0.19	0.19	0.56	-0.00	1	
IT	0.01	0.01	0.06	-0.28	0.34	1

Tab. 4 Maximum cross-correlation coefficient of monthly time series of landslides (L) with monthly indices of landslides (IL), precipitation (IP), wet days (ID), precipitation intensity (II), and temperature with variable m-month (m=1, 2, 3, 6, and 12)

m	IP	ID	II	IT
1	0.34	0.17	0.24	-0.06
2	0.32	0.18	0.19	-0.09
3	0.28	0.19	0.15	-0.09
6	0.22	0.20	0.12	-0.07
12	0.19	0.15	0.06	-0.06