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

3

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12

13 Abstract

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

24 For Calabria, the number of landslides is correlated to monthly precipitation, wet days and
25 precipitation intensity. Thus, landslide occurrence could be roughly forecasted using these climatic

26 data. Despite the favourable climatic trend, landslides are not decreasing because the recent
27 utilisation of landslide-prone areas increases the vulnerability.

28

29 Keywords: Landslides, climate change, Italy.

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

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

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

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

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

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

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

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

88 The *historical approach* is based on landslide observations and monitored climatic data, using
89 physical or statistical methods of analysis. In this case, the frequency, intensity, magnitude, and/or
90 duration of rainfall are taken into account, emphasising changing climatic conditions (Crozier
91 1997). Due to the starting date of gauge networks, this approach can be applied from the nineteenth
92 century (with country or regional differences) to the present. Even though this approach permits a
93 trend analysis (Petrucci *et al.* 2008), which is considered a fundamental prerequisite to evaluating
94 changes in landslide activity both in Europe (Dikau & Schrott 1999) and worldwide, scientific study
95 cases are not frequent. The reason for this could be the lack of historical data on landslides and/or
96 difficulties in collecting data (Dikau & Schrott 1999).

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

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

103

104 Methodological approach

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

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

112

113 The landslide database: data and elaborations

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

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

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

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

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

142

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

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

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

153

154 *Data validation.* One factor to take into account is the reliability of documents from which data
155 have been collected. In general, the reliability is affected by bias mainly when the document is a
156 refund request and/or the author is not an expert on landslides. The reliability classification of
157 documents presented in this work is usually general, but can be easily adapted to local peculiarities.
158 In this classification, reliability can be defined using sub-ranges, 0 to 1, 1 to 2, 2 to 3, and 3 to 4,
159 according to the type of document and the skill of the author. The highest reliability sub-range, 3 to
160 4, is used to characterise either scientific publications or governmental texts on the arrangement of
161 both first aid measures and long-term support for people living in affected areas (i.e., daily
162 allowance and temporary tax cuts for evacuated people). Scientific articles represent a very low
163 percentage of data sources, because they generally concern single landslide phenomena or
164 phenomena affecting selected territorial sectors, and they very often do not report the series of
165 landslide/s activations but rather the conditions at the moment when the article was written.

166 Reliability 2 to 3 is the sub-range for reports by technicians of departments in charge of damage
167 repair and refunding. In general, these technicians are engineers who assess the on-site type and/or
168 cost of remedial measures. Because they are trained and do not have any personal interest in the
169 distribution of refunds, their reports can be considered fairly reliable.

170 Reliability 1 to 2 is the sub-range typically used for reports of local technicians, as is the case for
171 refund request reports written by local authorities or damaged owners. This low reliability takes into
172 account the fact that the appraisal of damage can be stressed to increase the attention of the
173 governmental agency or insurance companies.

174 Reliability 0 to 1 classifies data obtained from historical books and newspapers. In these cases, both
175 the skill and individual experience of the document's author must to be taken into account. Both
176 reporters and historians are not expert in landslides, so they tend to emphasise the damage.

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

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

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

189

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

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

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

206

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

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

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

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

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

229

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

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

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

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

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

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

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

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

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

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

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

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

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

260 $IP_{12}(12,y)$ considers rainfall values observed in the whole hydrological year y, so it can be defined
 261 $IP(y)$, the *yearly precipitation index* of year y.

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

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

271 The range and variability interpretation of $ID_m(x,y)$ and $II_m(x,y)$ should be similar to those of
 272 $IP_m(x,y)$. As the monthly temperature can be negative and the variability is different and lower than
 273 the monthly rainfall parameters, the $IT_m(x,y)$ range should be the narrowest and almost symmetrical
 274 with respect to zero, whatever m value is considered.

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

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

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

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

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

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

286

287 The Calabria case study

288 Calabria, the southern-most Italian region (Figure 1), is a peninsula with a surface of 15 230 km², a
 289 perimeter of 738 km, and mean and maximum altitudes of 418 and 2266 m a.s.l. (Above Sea Level),
 290 respectively. Almost 90% of the regional territory shows topographic relief and 10% is represented
 291 by coastal and fluvial plains; 93.5% of the region is lower than 1300 m a.s.l. From an administrative
 292 point of view, the region is divided into five provinces, and 409 municipalities. The population
 293 density (133 inh/km²) is lower than the national value (198 inh/km²) (ISTAT 2003).

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

300

301 The LAND-Cal database

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

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

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

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

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

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

325 Analysing Figure 2, it can be noticed that most of the municipalities have been affected by between
326 1 and 10 landslide events. The peaks with more than 30 events represent some densely populated

327 municipalities located both near the coasts and in the central-western sector of the region (Petrucci
328 & Pasqua 2008).

329 Each year of the study period shows at least one event, and only five years show the minimum
330 value (1 case; 1922, 1924, 1931, 1943, and 1961). For the first four years, the low number of data
331 may be related to a data gap, also taking into account the low data availability in Calabria before the
332 1950's (the period in which regional newspapers appeared).

333 By dividing the study period into decades, the decade 1950-1959 records the highest number of
334 cases (699 cases, 23%): in this period, three particularly dramatic damaging hydrogeological events
335 affected Calabria (Petrucci *et al.* 2008). The minimum value was obtained for the decade 1920-1929
336 (125 cases, 4%). A high total number of cases characterises the periods 2000-2006 (419 cases, 14%,
337 in a 6-year period) and 1930-1939 (389 data, 13%). The mean value of data per decade is 320 cases
338 if the period 2000-2006 is excluded. For the whole study period, the maximum number of data per
339 municipality has an average of 10, but assessed by decade, it ranges from 5 for the first analysed
340 decade, to 20 for the period 2000-2006.

341 Dividing the study period in intervals of five years, the maximum value of landslides pertains to the
342 periods 2000-2004 (401 cases, 13%), 1955-1959 (381 cases, 12%) and 1950-1954 (318 cases,
343 10%).

344 November is the month characterised by the highest number of data (21%), followed by January
345 (14%) and February (14%) (Figure 3). More generally, 67% of data are recorded between
346 November and February. July is characterised by the lowest value (21 cases, 0.7%).

347 Figure 4 identifies the areas characterised by the highest landslide density and frequency. The
348 north-west sector has been highly affected by landslides, although of different intensities,
349 throughout the analysed sub-periods. Particularly in the decades 1950-1959 and 1980-1989, the
350 number of data per municipality shows some peaks with more than 6 landslide events per
351 municipality. The eastern side of the region, on the other hand, shows more than a decade
352 characterised by a low number of municipalities hit (1920-1929, 1940-1949, and 1960-1969), and,

353 more in general, the number of data per municipality per decade is lower than 6. The southernmost
354 sector of the region was affected by landslide events during each decade, also with peaks
355 characterising some densely populated municipalities located along the Tyrrhenian coast.

356

357 The CLIMATE-CAL database

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

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

374 The climate in Calabria is typically Mediterranean, characterised by hot and dry summers and long
375 wet periods in the autumn and winter, sometimes lasting until the early spring (Figure 3). The mean
376 annual precipitation ranges from 503 to 1778 mm (1172 mm as the regional spatial mean). The
377 spatial variability is mainly due to the altitude effect (Figures 1 and 4) and secondly to the distance
378 from the western coast (at same altitude the precipitation is higher on the regional western side), as

379 the main perturbations generally move from west to east (Petrucci & Polemio 2009). The annual
380 mean for D ranges from 54 to 118 mm (93 as regional mean), for I ranges from 7.3 to 13.8 mm/day
381 (11.1 mm/day as regional mean), and for T ranges from 8.9 to 18.7 °C (16.0°C as regional mean).
382 The spatial variability of these variables is mainly correlated to the altitude.

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

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

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

405 while ever since, the slope is progressively increasing, up to 2005, like for southern Italy (Polemio
406 & Casarano 2008).

407 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 .
408 For the sake of brevity, some statistical values of these time series are summarised in Table 2, for m
409 equal to 1 and 3; further details are highlighted in the paragraph of cross-analysis and discussion.

410 The complete understanding of landslide number trend should be pursued considering the
411 anthropogenic role. The attention should be focused on the increase of population number and
412 needs, deforestation, tillage, increasing cultivation and careless urban enlargement into natural
413 hazard prone areas, as observed for some areas of Calabria and southern Italy (Petrucci & Polemio
414 2007; Polemio in press).

415 Cross-analysis and discussion

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

424 Moving from mean monthly values to the yearly time series, these results are confirmed (Table 3).

425 In this case, the results are statistically identical either if L , defined as the yearly total number of
426 landslides in each cell of the region, or IL , is considered. CC^0 decreases from 0.46 to 0.19 moving
427 from IP to II . The correlation with IT is null and statistically not significant. For each variable, CC
428 decreases as l increases. IP is highly correlated with ID and II ; this result should be considered if a
429 forecasting model for L is defined using IP , ID , and II as independent variables.

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

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

440 On a ten-year basis, the mean number of landslides per decade is 320, if the period 2000-2006 is
441 excluded (Figure 4); a high total number of cases characterises the period 2000-2006 (419 cases,
442 14%, in a 6-year period). The minimum landslide number observed in the twenties (125 cases, 4%)
443 could be related to both ordinary precipitation and very few wet days (the 10-year moving average
444 defines the minimum value of ID in 1929). The peak landslide number observed in the thirties (389
445 data, 13%) seems justifiable in terms of both high precipitation and number of wet days (the 10-
446 year moving average defines the maximum value of IP in this decade).

447 It is possible to determine CC^l for the monthly time series of L with the monthly time series of each
448 index with a variable m value. The peak CC^l of each couple of time series is shown in Table 4. The
449 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
450 considered that the correlation with temperature is statistically not significant, while CC^l shows a
451 very low variability for $l \leq 4$ in the case of the ID_2 and ID_3 time series. The peak CC^l decreases as m
452 increases, apart from the negligible case of ID, in which it slightly increases. As a result, in terms of
453 monthly variability, the highest linear relationship of $IL_m(x,y)$ for month x',y' with $IP_m(x,y)$,
454 $ID_m(x,y)$, or $II_m(x,y)$, is, in practical terms, almost equal to that observed for $m=1$ for each time

455 series for the same month x',y' or for $l=0$. On this basis, the landslide number should be simply and
456 roughly forecasted using the monthly values of precipitation, wet days and precipitation intensity.

457

458 Conclusions

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

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

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

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

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

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

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

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

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

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604

605 FIGURE CAPTIONS

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

610

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

613

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

616

617 Fig. 4. Municipalities of Calabria classified according to the number of landslide data recorded in
618 the decades of the study period. (a) 1921-1929; (b) 1930-1939; (c) 1940-1949; (d) 1950-1959; (e)
619 1960-1969; (f) 1970-1979; (g) 1980-1989; (h) 1990-1999; (i) 2000-2006.

620

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

623
624

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

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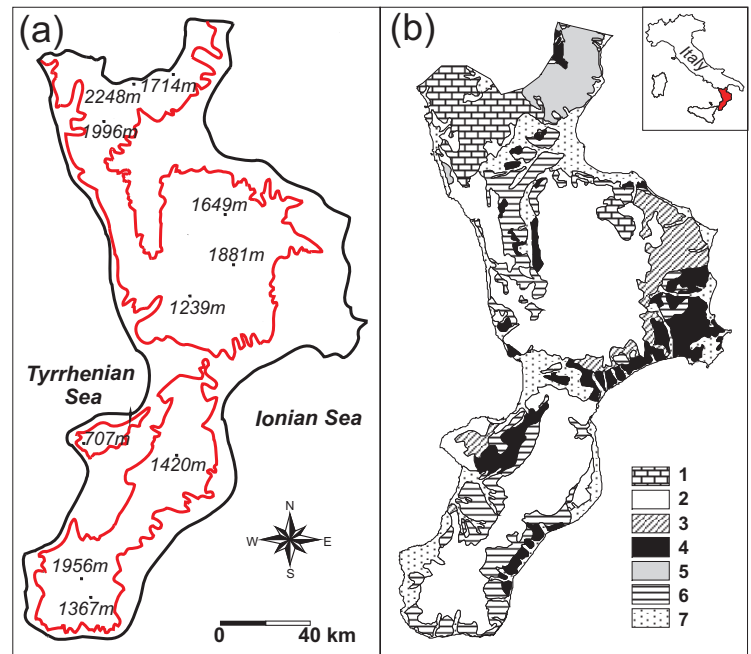


Figure 1

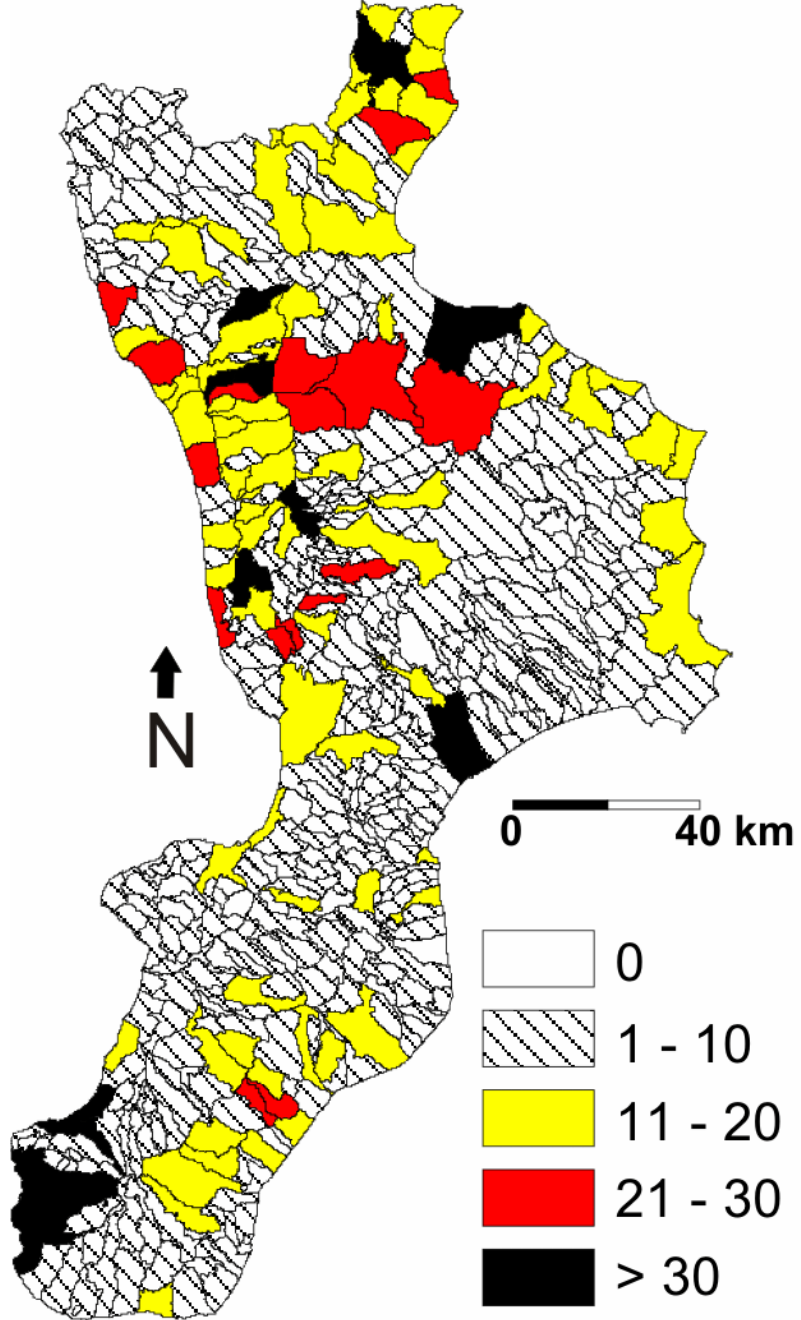


Figure 2

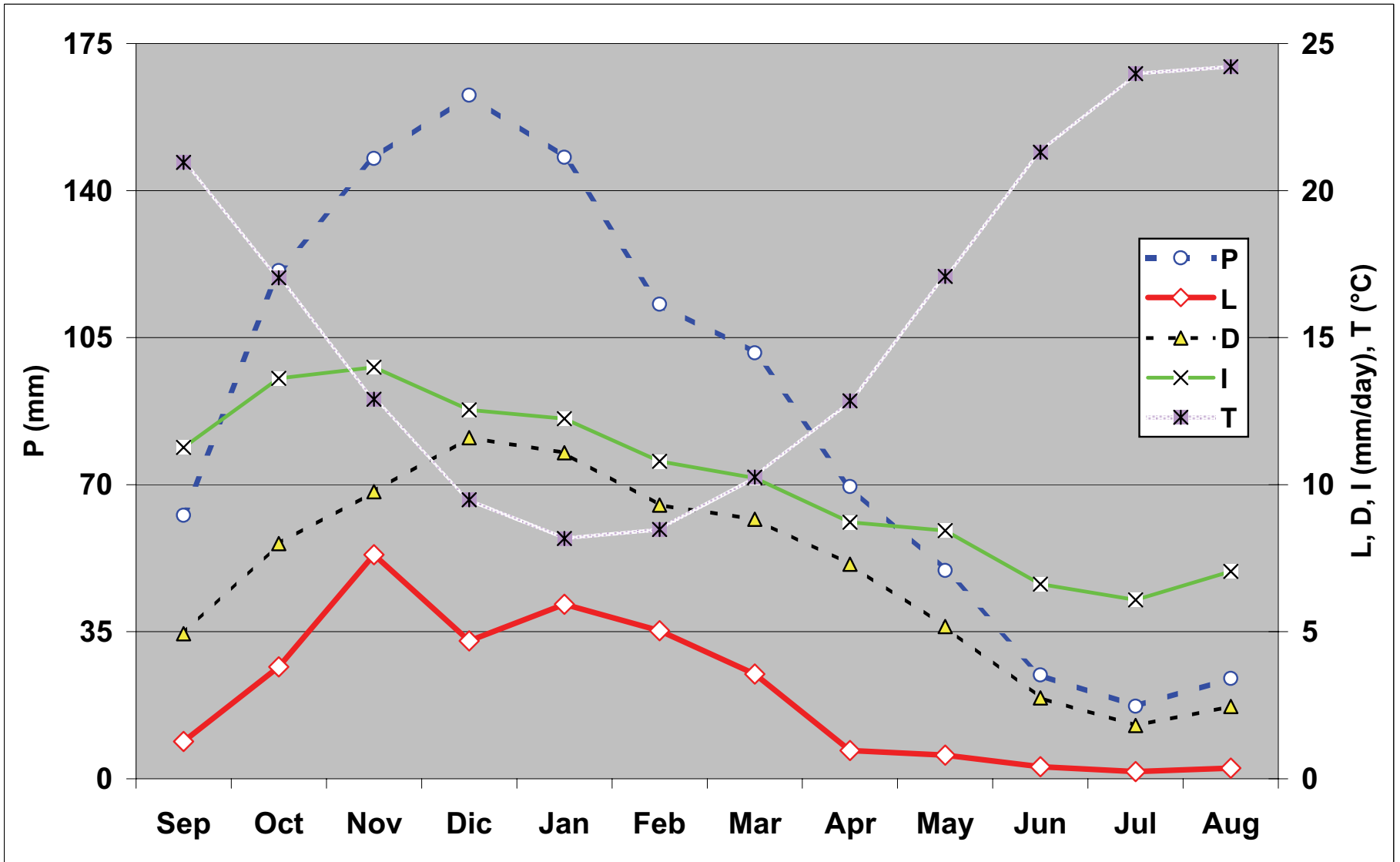


Figure 3

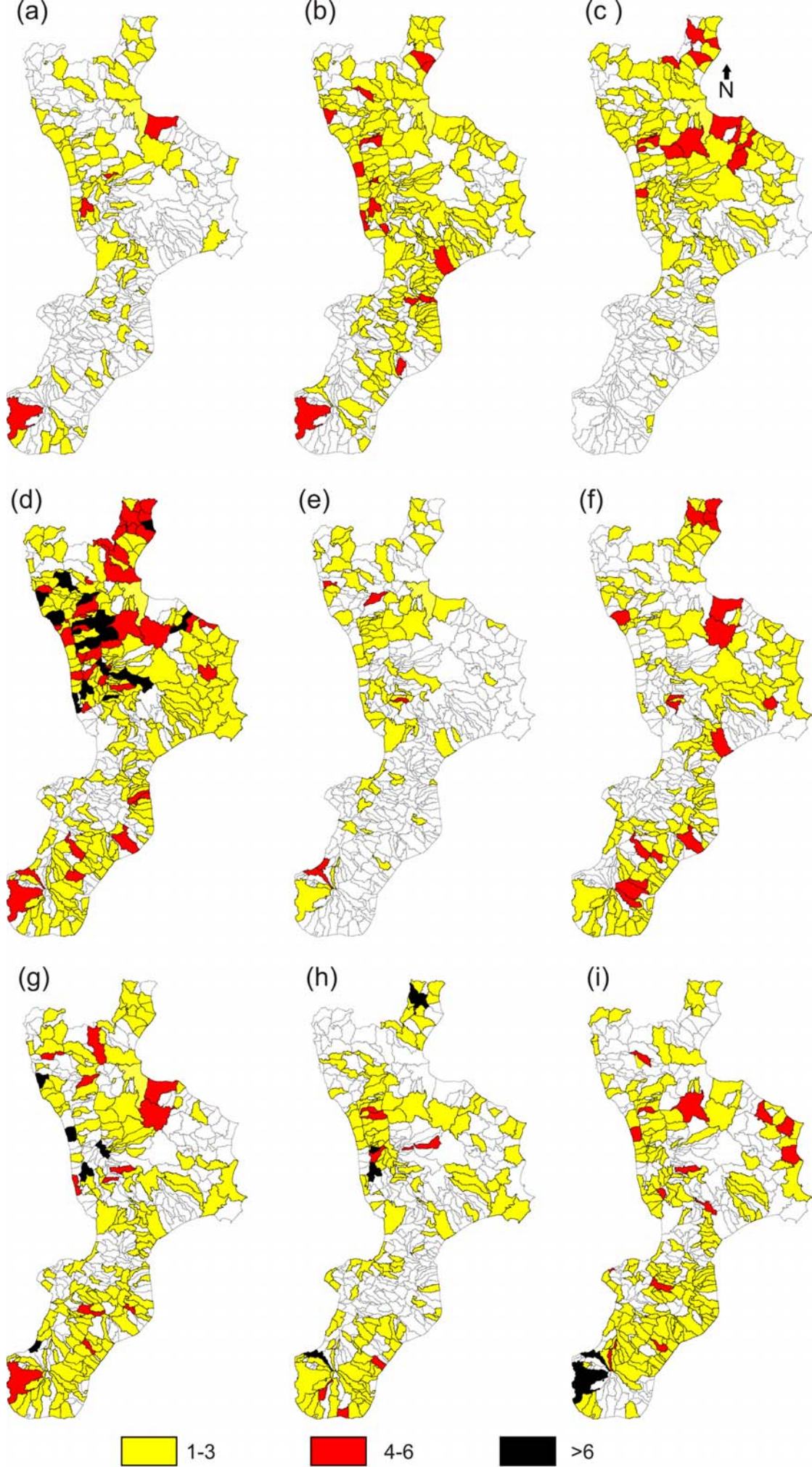


Figure 4

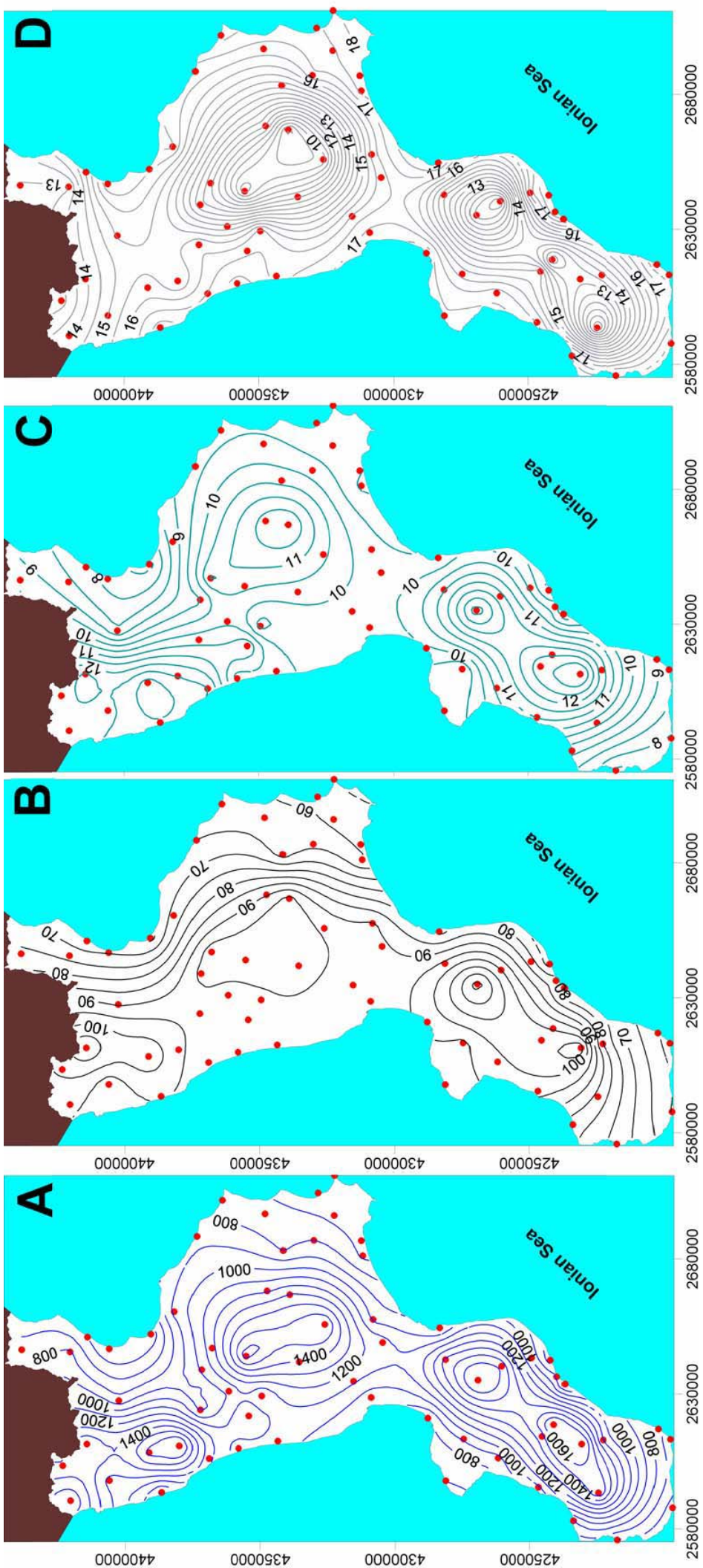


Figure 5

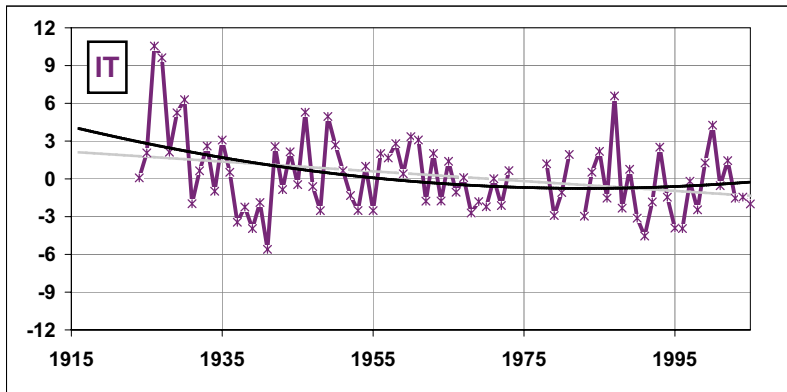
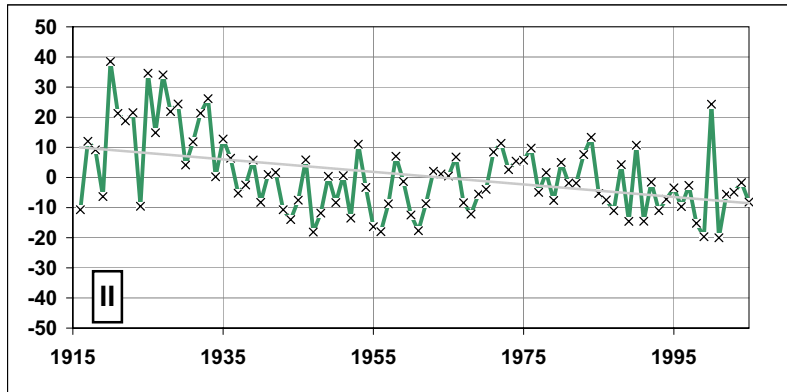
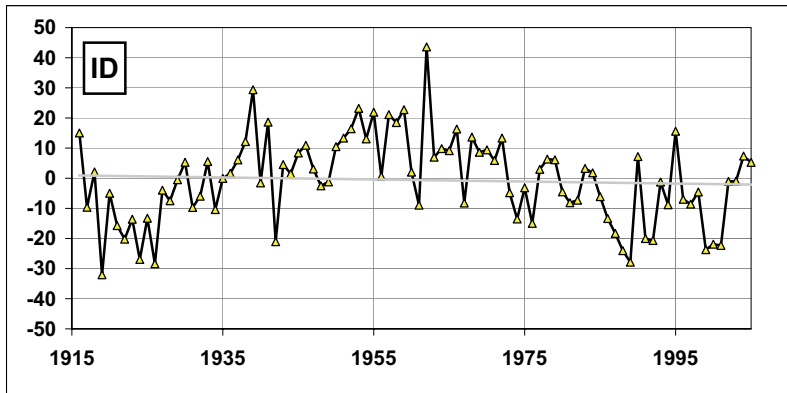
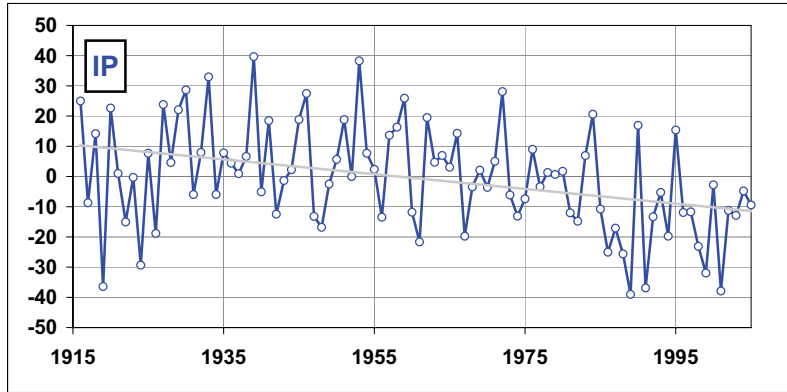
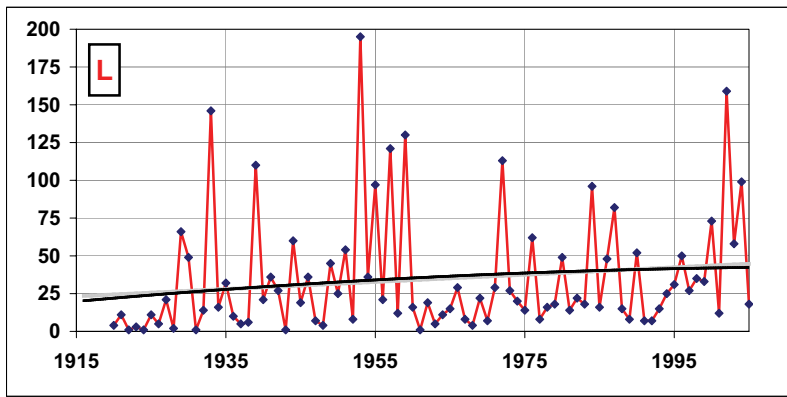


Figure 6

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