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Changes in the occurrence of rainfall-induced landslides in Calabria, southern Italy, in the 20th century

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Abstract. Only a few studies have investigated the geographical and temporal variations in the frequency and distribution of rainfall-induced landslides, and the consequences of the variations on landslide risk. Lack of information limits the possibility to evaluate the impact of environmental and climate changes on landslide frequency and risk. Here, we exploit detailed historical information on landslides and rainfall in Calabria, southern Italy, between 1921 and 2010 to study the temporal and the geographical variation in the occurrence of rainfall-induced landslides and in their impact on the population. We exploit a catalogue with information on historical landslides from June 1920 to December 2010, and daily rainfall records obtained by a network of 318 rain gauges in the same period, to reconstruct 448 493 rainfall events (RE). Combining the rainfall and the landslide information, we obtain a catalogue of 1466 rainfall events with landslides (REL), where an REL is the occurrence of one or more landslide during or immediately after a rainfall event. We find that (i) the geographical and the temporal distributions of the rainfall-induced landslides have changed in the observation period, (ii) the monthly distribution of the REL has changed in the observation period, and (iii) the average and maximum cumulated event rainfall that have resulted in landslides in the recent 30-year period 1981–2010 are lower than the rainfall necessary to trigger landslides in previous periods, whereas the duration of the RE that triggered landslides has remained the same. We attribute the changes to variations in the rainfall conditions and to an increased vulnerability of the territory. To investigate the variations in the impact of REL on the population, we compared the number of REL in each of the 409 municipalities in Calabria with the size of the population in the municipalities measured by national Censuses conducted in 1951, 1981, and 2011. We adopted two strategies; the first strategy considered impact as $I_{\mathrm{REL}} = \#\mathrm{REL} / P$, and the second strategy measured impact as $R_{\mathrm{REL}} = \#\mathrm{REL} \times P$, where #REL is the total number of REL in a period, and P is the size of the population in the same period and geographical area. The analysis has revealed a complex pattern of changes in the impact of rainfall-induced landslides in Calabria in the recent past, with areas where I_{REL} and R_{REL} have increased, and other areas where they have decreased. Municipalities where I_{REL} has increased are mainly in the mountains, and municipalities where R_{REL} has increased are mainly along the coasts. The complexity of the changes in the frequency and impact of rainfall-induced landslides observed in Calabria suggests that it remains difficult and uncertain to predict the possible variations in the frequency and impact of landslide in response to future climatic and environmental changes.

1 Introduction

In Italy, landslides are a serious threat to the population (Guzzetti, 2000; Guzzetti et al., 2005a, b; Salvati et al., 2010), with 3025 persons killed (1279), missing (15) or injured (1731) by landslides in the 50-year period 1954–2013. In Calabria, a region in southern Italy, landslides have killed 38 and injured 150 people in the same period (POLARIS, 2015). Of the 8103 municipalities in Italy, 656 (8 %) have experienced landslides with casualties (deaths, missing persons, injured people). The number of the municipalities in-

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creases to 1531 (19 %) if evacuees and homeless people are considered. In Calabria, 46 of the 409 municipalities (11 %) have experienced landslides with casualties in the period 1950–2013. Considering evacuees and homeless, the figure increases to 150 municipalities (37 %).

Rainfall is the primary trigger of landslides in Italy (Guzzetti et al., 1994; Trigila et al., 2010). To model the relationship between rainfall and landslide occurrence, a standard approach consists in the joint analysis of landslides and rainfall records to determine empirical rainfall thresholds for possible landslide occurrence (Reichenbach et al., 1998; Guzzetti et al., 2007, 2008). The approach assumes a stationary (in time) relationship to link landslide occurrence to rainfall measurements (Reichenbach et al., 1998; Guzzetti et al., 2007). However, rainfall conditions that have resulted in landslides in the past may change over long periods, or may vary in the future due to environmental and climatic changes, including changes in rainfall intensity and frequency, and in the pattern of the meteorological triggering events. Variations in the frequency and intensity of the rainfall events will affect the frequency of rainfall-induced landslides (Crozier, 2010). An increase in the frequency and the intensity of extreme rainfall events was observed in several geographical regions in the world (IPCC, 2013), including Italy (Brunetti et al., 2002). Temporal variations in the rainfall conditions that result in landslides can jeopardise the definition and the application of empirical rainfall thresholds for the prediction of landslide occurrence (Guzzetti et al., 2007, 2008).

Only a few studies have investigated the geographical and temporal variations in the frequency and distribution of rainfall-induced landslides (e.g., Reichenbach et al., 1998; Mathie et al., 2007; Polemio and Petrucci, 2010; Chiang and Chang, 2011; Lollino et al., 2014; Stoffel et al., 2014), and the consequences of the variations on landslide risk (Guzzetti et al., 2005b; Salvati et al., 2010). Lack of information limits the possibility to evaluate the impact of the expected environmental and climate changes on landslide frequency, and the related risk. In an effort to fill this gap, we exploit detailed historical information on landslides and rainfall in Calabria, southern Italy, in the 90-year period 1921–2010 to study the temporal and the geographical variations in the occurrence of rainfall-induced landslides and in their impact on the population, and we investigate some of the natural (i.e., rainfall) and human (i.e., population density) causes of the changes.

2 Background

In the literature, the analysis of the effects of climatic and environmental changes on landslide activity is performed using modelling or empirical approaches (Crozier, 2010). The modelling approach investigates variations in the stability/instability conditions of single landslides driven by records of rainfall and/or pore pressure measurements, and attempts to predict variations in the stability/instability conditions of slopes using synthetic, future rainfall records obtained from downscaled global climate models (Buma and Dehn, 1998, 2000; Dehn and Buma, 1999; Dehn et al., 2000; Comegna et al. 2013; Rianna et al., 2014). The empirical approach exploits records of landslide occurrences to determine variations in the activity or the frequency of the landslides, and can be separated in two groups depending on the period covered and the tools used to construct the records of the landslide occurrences. An approach exploits palaeoenvironmental evidences to construct landslide records and to analyse periods of increased/decreased landslide activity. Adopting this approach and exploiting ^{14}C dating techniques, Bertolini (2007) obtained a catalogue of 20 landslide events in the Emilia-Romagna region, northern Italy, in the last 10 000. Similarly, Borgatti and Soldati (2010) (using stratigraphic methods and ^{14}C dating techniques) dated landslides of different types in the Italian Dolomites in the late-glacial–Holocene transition period, and attributed the cluster of the landslides to increased permafrost melting.

Another approach consists in the comparison of catalogues of historical landslide occurrences to records of river discharge or rainfall measurements. Reichenbach et al. (1998) used a catalogue of historical landslide and flood events in the Tiber River basin, Italy, and records of mean daily discharge at different gauging stations in the same catchment between 1918 and 1990, to determine regional hydrological thresholds for landslide and flood occurrence. Stoffel et al. (2014) analysed changes in the frequency and seasonal distribution of shallow landslides in Piedmont, NW Italy, from 1960 to 2011, and identified two periods of increased landslide frequency that they attributed to an increase in the mean annual temperature. Polemio and Petrucci (2010) studied monthly rainfall (and temperature) records in Calabria from 1921 to 2006, and determined that landslide occurrence did not decrease in the region in their observation period, despite a decrease in the monthly total rainfall.

A difficulty in the application of the empirical historical approach lays in the availability of accurate records of historical landslide events. In many areas, accurate and sufficiently complete records of rainfall measurements are available for long (multi-decadal) periods. However, landslide records are not commonly available for comparatively long periods (Guzzetti, 2000; Guzzetti et al., 2005b). Further, the completeness and quality of the landslide records varies with time (Petrucci and Pasqua, 2008; Petrucci and Gullà, 2010), depending on the abundance and type of the historical and recent sources, and the skill of the investigators (Lang et al., 1999; Guzzetti et al., 1994, 2005a).

A limited number of global catalogues lists information on landslides and floods, including (i) the *Emergency Events Database* (EM-DAT) maintained by the Centre for Research on the Epidemiology of Disasters of the Université Catholique de Louvain, (ii) the *Natural Hazards Assessment Network* (NATHAN) prepared by Munich Re, and (iii) the recent *Global Landslide Catalogue* prepared by the U.S. National Aeronautic and Space Administration (NASA), which lists information on rainfall-triggered landslides since 2007 (Kirschbaum, 2014). These catalogues focus on major catastrophic events, and the number of the listed landslides is known to be underestimated, largely (Llasat et al., 2013a, b).

In Italy, abundant information exists on historical landslides. An inventory of historical landslides was first prepared in the framework of the AVI – Aree Vulnerate Italiane (an acronym for Areas Affected by Landslides or Floods) national project to cover the period 1917–1990 (Guzzetti et al., 1994), and was next updated to cover the period 1900–2002 (Guzzetti and Tonelli, 2004). Guzzetti (2000) prepared a catalogue of historical landslides with direct human consequences from 1279 to 1999. The catalogue was revised and extended by Salvati et al. (2003, 2010) and by Guzzetti et al. (2005a, b). Recently, Brunetti et al. (2015) compiled a catalogue of 1981 rainfall events that have resulted in at least 2408 shallow landslides in Italy in the period 1996–2012. In addition, a number of regional and local catalogues of landslide events exists in Italy, including catalogues for e.g., the Emilia-Romagna (Emilia-Romagna SGSS, 2015), Umbria (Salvati et al., 2006), and Calabria (Petrucci and Versace, 2005, 2007; Petrucci et al., 2009; Palmieri et al., 2011) regions.

3 Method

We base our analysis of the possible variations in the rainfall-induced landslides in Calabria on two sources of information collected in the region, including: (i) a database of daily rainfall measurements, and (ii) a record of occurrences of rainfall-induced landslides. Both sources cover the 90-year period 1921–2010. Our approach relies on the construction and analysis of three catalogues: (i) a catalogue of landslide events, (ii) a catalogue of rainfall events, and (iii) a catalogue of rainfall events with landslides.

We first define a landslide event (LE) as the occurrence of one or more landslides in a given municipality and in a given date (day, month, year). In the literature, no clear definition exists for a rainfall event (RE), and no common criteria exist to single out RE from rainfall records (Melillo et al., 2015). In this work, we define a rainfall event (RE) as a continuous sequence of rainy days (i.e., days with cumulated daily rainfall > 0 mm) preceded and followed by at least 1 dry day (i.e., a day with no measured rainfall, Gullà et al., 2012). We further define a rainfall event with landslides (REL) as the occurrence of a LE during or immediately after an RE. To single out the individual REL, we use two criteria. First, the geographical distance between the LE and the location of the rain gauge where the event is determined shall be < 5 km. Where two or more rain gauges meet this criterion, we select the rain gauge closest to the landslide. Second, the date of the LE must be between the start and the end dates of the RE, or no more than 1 day after the end of the RE. The starting date of the REL corresponds to the start date of the RE. The end date of REL is (i) the day when the rainfall-induced landslide occurred (if the landslide occurred between the start and the end dates of the RE) or (ii) the end date of the RE (if the landslide occurred in the day following the end day of the RE).

Our analysis also relays on the definition of empirical rainfall thresholds for possible landslide occurrence in Calabria. To define the rainfall thresholds we adopt the method proposed by Brunetti et al. (2010) and modified by Peruccacci et al. (2012), where the threshold curve is a power law relationship linking the rainfall duration D to the cumulated event rainfall $E = (\alpha \pm \Delta\alpha) \cdot D^{(\gamma \pm \Delta\gamma)}$, α is a scale parameter that defines the intercept of the power law threshold model, γ is the shape parameter that defines the slope of the power law model, and $\Delta\alpha$ and $\Delta\gamma$ represent the uncertainties of α and γ, respectively. The method allows defining thresholds for different exceedance probabilities. For our analysis, we define 5 % thresholds (T_5) i.e., threshold lines that leave 5 % of the (D, E) empirical points below the threshold.

4 Study area

Our study area is Calabria, a region in southern Italy that extends for 15 080 km^2 (Fig. 1a) and comprises 409 municipalities ranging in size from 2.4 to 292.0 km^2 (average 38.4 km^2). Elevation in the region ranges from sea level to 2260 m a.s.l., and morphology is shaped by a tectonic uplift initiated in the Quaternary and that remains active. Allochthonous crystalline rocks, Palaeozoic to Jurassic in age, stacked over carbonate units in the middle Miocene, represent the backbone of the region, with Neogene flysch filling tectonic depressions (Tortorici, 1982; Monaco and Tortorici, 2000). Mean annual rainfall averages 1150 mm in the region, with the Ionian (E) side of the region less rainy than the Tyrrhenian (W) side (Terranova, 2004) (Fig. 1b). Annual rainfall depends strictly on elevation, with the mountains significantly wetter (> 1400 mm) than the coastal plains (< 1000 mm). About 70 % of the annual rain falls from October to March, and 10 % in the summer. Rainfall events with large cumulated rainfall occur mainly between November and January, whereas high intensity events are most common in September and October (Terranova and Gariano, 2014).

A number of studies have investigated variations in the rainfall patters and trends in Calabria. Ferrari and Terranova (2004) revealed a reduction in the annual and the winter amounts of rainfall for two overlapping periods (1920–2000 and 1960–2000), and Caloiero et al. (2011) recognised an augmented trend in the summer rainfall. Caloiero et al. (2008) showed that short-duration rainfall events were most frequent in November between 1921 and 1960, and in October between 1961 and 2000. Brunetti et al. (2012) observed a marked decrease in the cumulated annual rainfall in the period 1916–2006, particularly in the E (Ionian) side of the region, and attributed the decrease to a negative trend in the monthly rainfall in the autumn–winter period, whereas in the summer the tendency is toward an increase of the cumulated rainfall.

5 Description of the catalogues

5.1 Catalogue of landslide events

To compile the catalogue of landslide events (LE) we used different sources of information, including local and national newspapers, web sites, reports from national and regional agencies and public offices, and post-event field surveys (Petrucci and Versace, 2005, 2007; Petrucci et al., 2009; Palmieri et al., 2011). Each record in the LE catalogue lists: (a) a LE identification number, (b) the date (and time when available) of occurrence of the landslide(s), (c) the geographical location of the landslide(s), (d) a short description of the landslide(s), (e) an indication of whether a "single" or "multiple" (two or more) landslides were reported, and (f) qualitative information on the size ("small" or "large) of the reported landslide(s).

Overall, the catalogue lists information on 7600 LE from June 1920 to December 2010 (on average 84 LE per year, 7 LE per month). Not all the records in the catalogue contain all the information. Information on the geographical location of the landslide(s) consists in the geographical coordinates of the site(s) where the landslide(s) has (have) occurred (available for 23 % of the LE), or in the geographical coordinates of the centroid of the municipality where the landslide(s) was (were) reported (available for 77 % of the LE).

Figure 2a shows the number of LE in each of the 409 municipalities in Calabria. The average number of LE per municipality is 17, with 146 municipalities with less than 10 LE, and three municipalities (Torre di Ruggiero, Simbario, Spadola) with only one LE. Four municipalities experienced more than 100 LE, including Catanzaro (142 LE), Cosenza (120), Reggio Calabria (117), and Scilla (104). We note that the municipalities of Reggio Calabria, Catanzaro and Cosenza (Fig. 1a) host the three largest and most populated cities in the region. The two adjoining municipalities of Scilla and Bagnara Calabra, along the SW coast of the region, together were affected by 190 LE, most of which occurred along the SS18 national road and the national railway connecting southern Calabria to Central Italy (Diodato et al., 2011; Petrucci and Pasqua, 2013; Iovine et al., 2014).

Figure 2b portrays the temporal distribution of the LE. The average number of LE per year is 67. For 15 years in the catalogue, less than 10 LE were recorded. We consider these years as characterised by low landslide impact. For 17 years in the catalogue, 100 or more LE were recorded. We consider these years as years with a high landslide impact, including 2009 (492 LE) and 2010 (499). The 3 single days with the largest number of reported LE were 30 November 1933

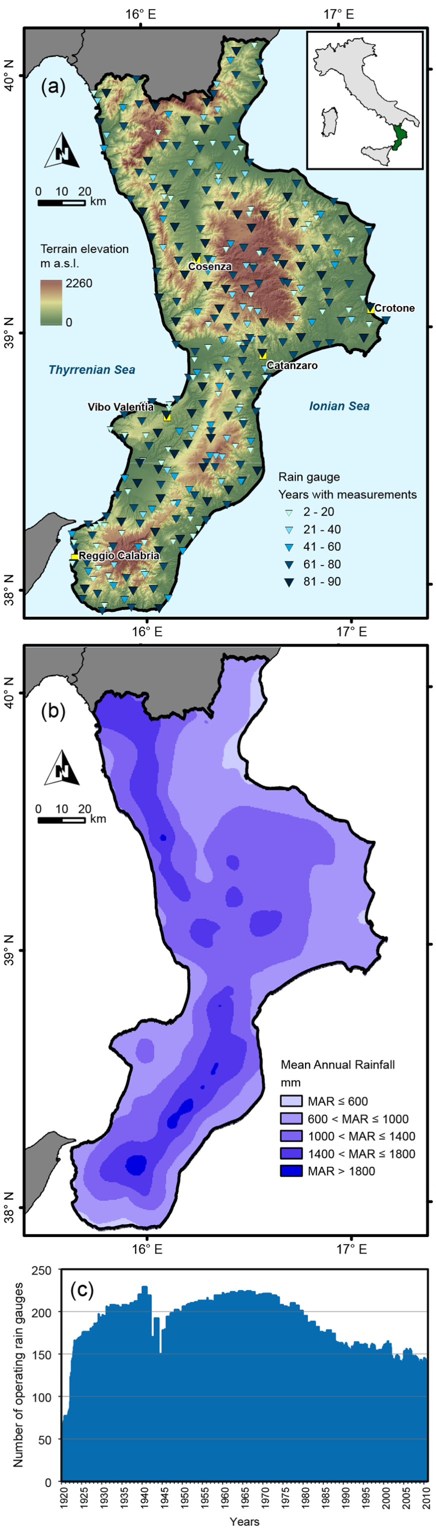

Figure 1. (a) Map of Calabria, southern Italy, showing terrain elevation (shades of green to brown), main cities (yellow squares), and location of rain gauges used in the study (triangles). Shades of blue show number of years with measurements for each rain gauge, in five classes. **(b)** Map of mean annual rainfall (MAR) in Calabria, in five classes. **(c)** Number of operating rain gauges per year in Calabria between 1920 and 2010.

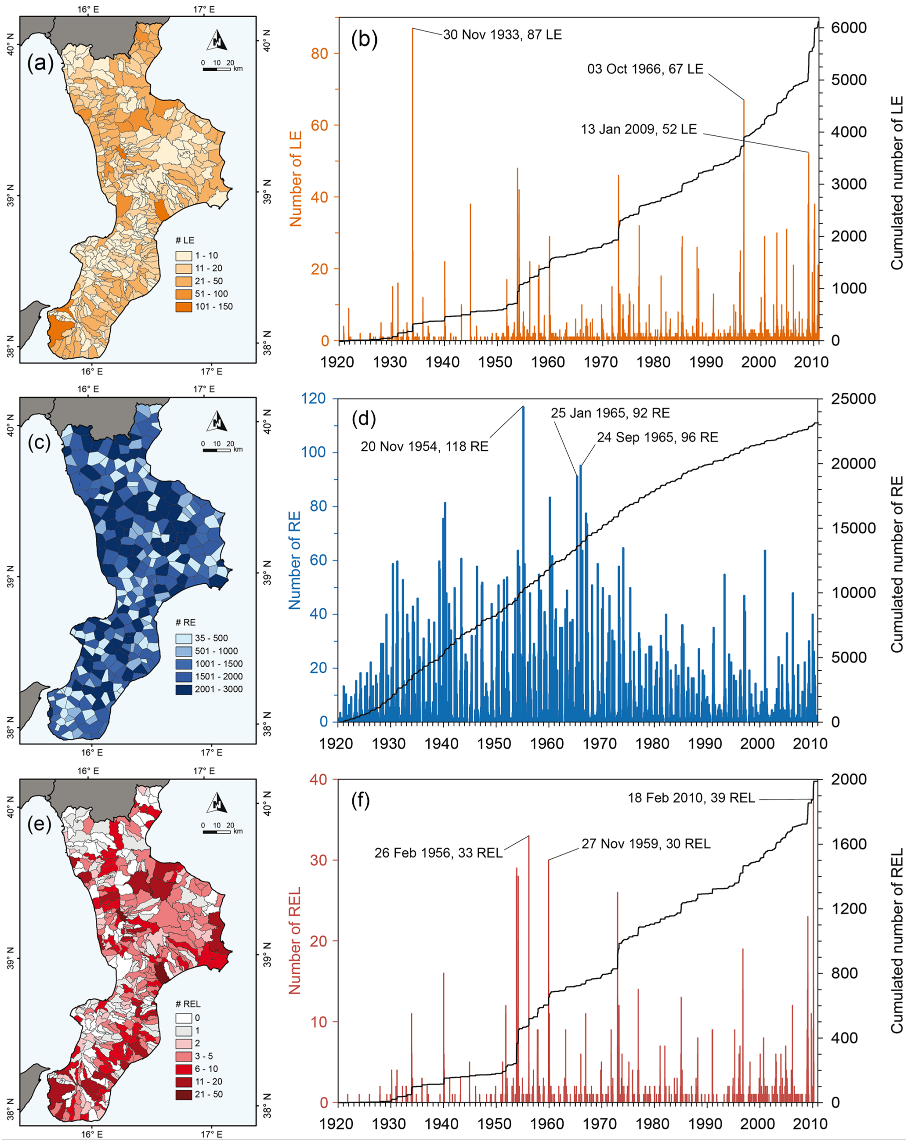

Figure 2. (a) Number of landslide events (LE) in each municipality in Calabria in the 90-year period 1921–2010. **(b)** Temporal distribution of LE (orange bars), and cumulated number of LE (black line) in the period 1921–2010. The 3 single days with the largest number of LE are shown. **(c)** Number of rainfall events (RE) reconstructed for each rain gauge in the period 1921–2010. Reference area for each rain gauge is shown using Thiessen polygons. **(d)** Temporal distribution of reconstructed RE (blue bars), and cumulated number of RE (black line) in the period 1921–2010. The 3 single days with the largest number of RE are shown. **(e)** Number of rainfall events (REL) in each municipality in the period 1921–2010. **(f)** Temporal distribution of REL (red bars), and cumulated number of REL (black line). The 3 single days with the largest number of REL are shown.

(87 LE), 3 October 1996 (67), and 13 January 2009 (52). The cumulated number of LE (black line in Fig. 2b) measures the completeness of the historical catalogue (Guzzetti, 2000; Wood et al., 2015). In the early period 1910–1950, the cumulated curve exhibits a slope lower than in the later period 1950–2010. We interpret this as an indication that the catalogue is more complete in the recent part (after 1950) and less complete in the older part of the series.

5.2 Catalogue of rainfall events

To obtain the catalogue of rainfall events (RE) we used rainfall measurements captured by a network of 318 rain gauges in Calabria (Fig. 1a) between 1 January 1920 and 31 December 2010. On average, the single rain gauges operated for 47 years, with 13 rain gauges (4.0 %) that operated for the entire 90-year period, and three rain gauges (0.9 %) with only 2 years of measurements. Figure 1c shows the number of rain gauges per year in the observation period. From the mid-

1920s to 2010, at least 150 rain gauges were operational every year. The largest number of rain gauges (> 200) was available in the 1930s, and between 1950 and 1975, whereas a minimum number of gauges was available in the early 1940s, during the Second World War. A decrease in the number of the available rain gauges was observed in the most recent years (from 2000), and is due to the replacement of old rain gauges with new, automatic gauges, many of which were located in places different from the old gauges.

We adopted strategies to consider and mitigate the effects of the heterogeneity inherent to the rainfall measurements. We obtained the database of rainfall measurements used in the study from the "Centro Funzionale Multirischi" of the Environmental Protection Agency of Calabria (http://www.cfd.calabria.it/) that distributes the data after validation. This contributes to reduce heterogeneity. In a study of climate variation in Calabria between 1916 and 2006, Brunetti et al. (2012) analysed 173 rain gauges from the same rainfall database, and found that the rainfall records were homogeneous for 87 rain gauges (50 %) and required homogenization for 42 rain gauges (24 %). The other 44 rain gauges (26 %) were discarded for the climatic research. Our work is based on daily measurements or short sequences of daily measurements. We therefore expect that the number of rain gauges characterised by homogeneous records is larger. Also, the "gap filling" procedures used to homogenise the rainfall records for climatic research (Brunetti et al., 2012) may not work effectively for short-duration, intense and localised rainfall events. Different rain gauge stations may have different measurement accuracies, affecting the minimum measured rainfall, a possible cause of heterogeneity. We note that all the rain gauges used in our study have the same nominal accuracy (0.2 mm). This contributes to reduce heterogeneity. To mitigate further the effects of heterogeneity caused by the use of different measuring instruments at the same location, we excluded from the analyses the measurements obtained by the new automatic gauges. Where new gauges replaced old gauges the historical rainfall record was interrupted, and we used only the part of the record obtained by the old gauges.

Exploiting the rainfall information available to us, and adopting the approach proposed by Gullà et al. (2012), we reconstructed 448 493 rainfall events (RE) in the 90-year observation period. This is an average of about 4893 RE per year, with a maximum of 7760 (1.7 %) RE in 1964. For each RE we determined (a) the start and the end date of the event, (b) the rain gauge where the RE was detected (with an event referred to a single rain gauge), (c) the event duration (D, in days), and (d) the cumulated event rainfall (E, in mm). Of all the reconstructed events, 231 200 (47.5 %) have cumulated event rainfall $E \geq 10$ mm, and 23 146 (5.2 %) $E \geq 100$ mm. For the latter events, the average rainfall duration D is 7 days (mode 5 days, median 6 days), with a minimum of 1 day and a maximum of 131 days (4.4 months). The average cumulated event rainfall E is 169 mm, with a maximum $E = 1650$ mm, for a rainfall duration $D = 61$ days.

Figure 2c shows the number of RE per rain gauge. A reference area based on Thiessen polygons was assigned to each rain gauge. The average number of RE per rain gauge is 1240, with a maximum of 2822 RE for the Catanzaro rain gauge. For 84 rain gauges, located mainly in the N part of the region, more than 2000 RE were reconstructed. Figure 2d shows the number of severe RE ($E \geq 100$ mm) per year. On average, 254 severe RE were reconstructed every year, with a maximum of 604 severe RE in 1954, and a minimum of 67 severe RE in 1991. Inspection of the cumulated number of RE (black curve in Fig. 2d) reveals a constant rate from the beginning of the record (1920) the end of the 1990s. We attribute the gentle decrease in the frequency of the RE in the last decade to the reduction in the number of the rain gauges (Fig. 1c). However, lack of significant changes in the rate of the RE, measured by the local slope of the cumulative curve, suggests a uniform reconstruction of the RE, in the considered period.

Figure 3a shows the number of severe RE per year in the 90-year observation period. The average value per year is 28, and was exceeded 43 times, of which 15 times in the 1921–1950 period, 18 times in the 1951–1980 period, and 10 times in the 1981–2010 period. The 1951–1980 period was characterised by the largest average number of severe RE per year (318). The maximum number of severe RE (609) was recorded in 1954, and the minimum (79) in 1922. In six years (1930, 1933, 1940, 1954, 1973, 1996) the number of reconstructed severe RE was larger than 500.

5.3 Catalogue of rainfall events with landslides

Using the method presented in Sect. 3 we reconstructed 1989 REL in Calabria between October 1921 and December 2010. The REL have an average duration $D = 6$ days, and an average cumulated event rainfall $E = 157.5$ mm. The reduced number of REL (1989) compared to the number of LE (7600) has many reasons. First, many landslides listed in the LE catalogue were not triggered by rainfall. In some cases they were triggered by earthquakes (e.g., in 1947), and in other cases by human activities. These LE were excluded from the analysis. Second, in some cases the rain gauges failed to measure or to record the rainfall, and the landslide information could not be used to reconstruct an REL. Third, for small shallow landslides triggered by intense, short-duration rainfall events lasting only a few hours, the daily rainfall measurements were not adequate to identify a triggering event, and the REL were not determined. Fourth, for some of the old events uncertainty in the date of the slope failure resulted in a mismatch between the landslide and the daily rainfall record, and the REL could not be determined. Finally, we discarded from the analysis all the RE with mean rainfall intensity < 10 mm day^{-1}. The value was selected heuristically, following Terranova and Gariano (2014), to exclude from

Table 1. Summary statistics for rainfall events with landslides (REL) in Calabria for the entire catalogue, and for different periods and landslide subsets. Legend: #REL, number of rainfall events with landslides; D, duration of a rainfall event (in days); E, cumulated event rainfall (in mm).

Data set	#REL	D (days)			E (mm)		
		min	mean	max	min	mean	max
Entire catalogue	1466	1	7	32	10.0	202.3	1504.7
Single landslides	534	1	7	32	10.0	182.6	977.1
Multiple landslides	932	1	7	24	10.0	213.6	1504.7
Small landslides	610	1	7	28	10.0	185.2	977.1
Large landslides	314	1	8	32	10.9	200.0	1216.2
Winter	728	1	8	32	10.0	178.5	914.5
Spring	84	1	5	19	10.0	127.1	483.2
Summer	32	1	3	5	10.6	171.5	443
Autumn	622	1	6	28	11.0	241.9	1504.7
Wet period	1159	1	7	32	10.0	187.0	1216.2
Dry period	307	1	5	19	10.0	259.9	1504.7
1921–1950	143	1	7	28	11.1	232.1	1216.2
1951–1980	720	1	7	24	10.0	225.7	1504.7
1981–2010	603	1	7	32	10.0	167.2	914.5

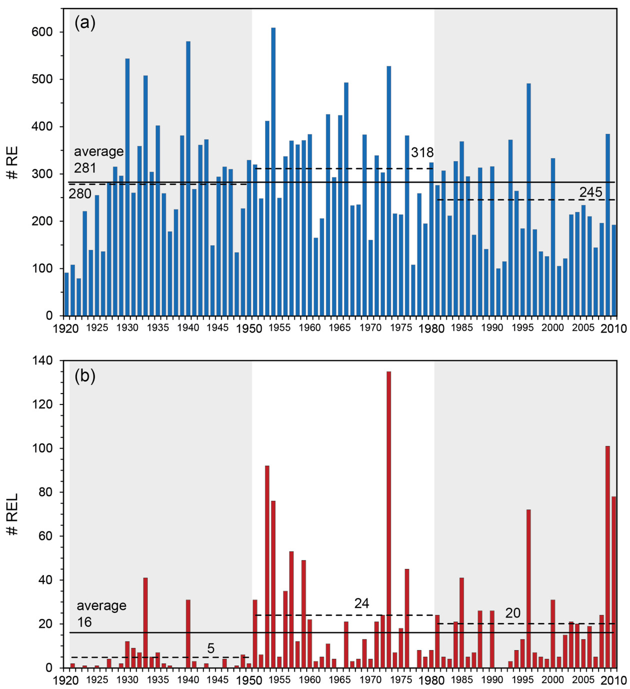

Figure 3. (a) Number of rainfall events (RE) and **(b)** number of rainfall events with landslides (REL) per year in Calabria in the 90-year period 1921–2010. Solid lines show average values for the 90-year period. Dashed lines show average values for the three 30-year periods 1921–1950, 1951–1980, and 1981–2010.

the analysis less significant events. The remaining 1466 RE with landslides have durations in the range $1 < D < 32$ days (average 7 days), and cumulated event rainfall in the range $10.0 < E < 1504.7$ mm (average 202.3 mm) (Table 1).

Figure 2e shows the number of REL per municipality. The average number of REL in a municipality is four, the minimum is zero (95 municipalities, located chiefly in the N part of the region and along the SW coast), and the maximum is 47, in the Catanzaro municipality (Fig. 2e). More than 30 municipalities experienced 10 or more REL in the investigated period. Figure 2f portrays the number of REL per year. On average, 16 REL occurred every year with a maximum of 139 REL in 1973. The 3 days with the largest number of REL were 18 February 2010 (39 REL), 29 February 1956 (33), and 27 November 1959 (30). The month with the largest number of REL was January (337), followed by November (255), and February (254). The decades with the largest number of REL were those between 1950 and 1959, between 1970 and 1979, and between 2000 and 2009. Inspection of the cumulated number of REL (black curve in Fig. 2f) reveals that in the early period 1910–1950, the rate of the REL is lower than in the later period 1950–2010. This is a result of the different completeness of the information of the LE (Fig. 2b).

Figure 3b shows the number of REL per year in the 90-year observation period. For six years more than 60 REL were recorded: 1973 (135 REL), 2009 (101), 1953 (92), 2010 (78), 1954 (76), and 1996 (72). The average value (16 REL per year) was exceeded 28 times: twice in the 1921–1950 period and 13 times in each of the following 30-year periods. The intermediate (1951–1980) and the recent (1981–2010) periods were characterised by average number of REL per year equal to 24 and 20, respectively. In both cases the values are larger than the 90-year average (16).

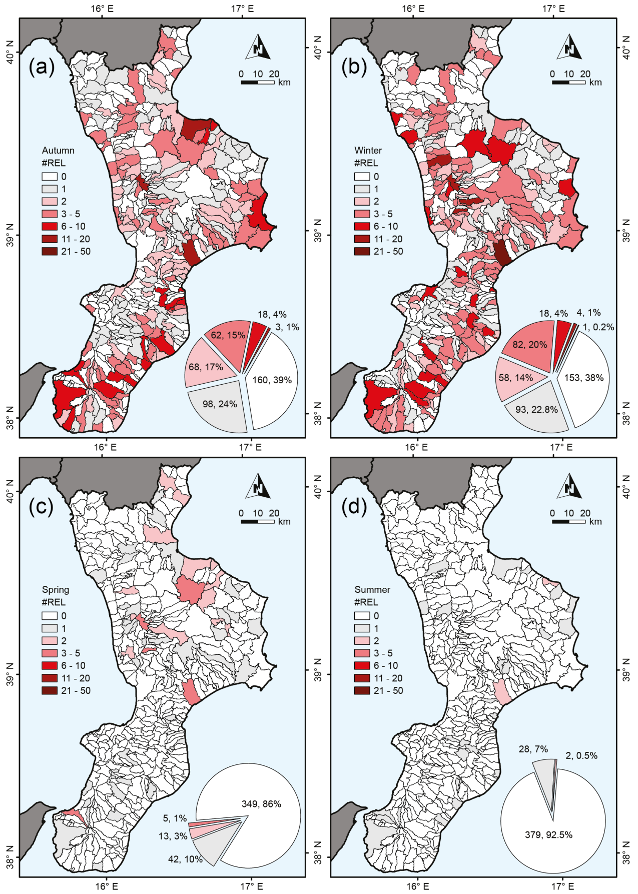

Figure 4. Maps show the number of rainfall events with landslides (#REL) per municipality in Calabria in the **(a)** Autumn (22 September–20 December), **(b)** Winter (21 December–20 March), **(c)** Spring (21 March–20 June), and **(d)** Summer (21 June–21 September). Pie charts show number and percentage of municipalities in each seasonal class.

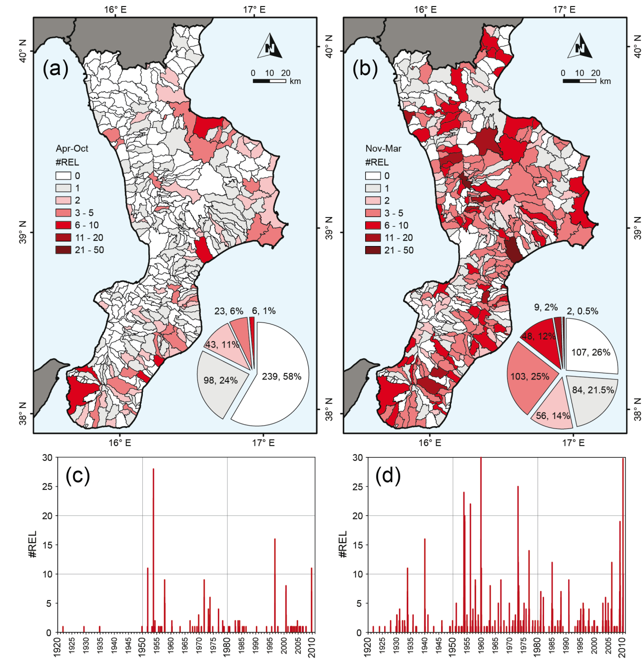

Figure 5. Top: Maps show the number of rainfall events with landslides (#REL) per municipality in Calabria in **(a)** the dry period (April to October) and **(b)** in the wet period (November to March). Pie charts show number and percentage of municipalities in each class. Bottom: Bar charts show temporal distribution of REL in the **(c)** dry and in the **(d)** wet periods.

6 Analysis of rainfall events with landslides

Our catalogue lists 1466 severe REL in Calabria from October 1921 to December 2010, of which 534 (36.4 %) have triggered "single" landslides and 932 (63.6 %) "multiple" landslides. We acknowledge uncertainty in the classification of an REL as having triggered a "single" landslide. Indeed, a "single" landslide REL may have triggered multiple landslides and the information may not be available to us. Conversely, REL with "multiple" landslides are certain, because they have triggered two or more landslides. We note that REL with "single" landslides have average and maximum cumulated event rainfall E lower than REL with "multiple" landslides (Table 1). Even considering the uncertainty in the classification of REL associated to "single" landslides, the finding was expected because some of the REL with "multiple" landslides have triggered several or many landslides, as a result of severe rainfall conditions. For 924 REL (63.0 %), qualitative information exists on the size of the landslides, with 610 REL (41.6 %) that have resulted in "small" landslides, and 314 REL (21.4 %) that have caused "large" landslides. As expected, REL that have resulted in "small" landslides have (on average) D and E values lower than REL that have caused "large" landslides (Table 1).

We investigated the spatial and temporal distributions of the REL listed in our catalogue, and their temporal variations. For the purpose, we segmented the catalogue considering (i) the four seasons, (ii) two seasonal periods (i.e., "dry" and "wet" period proposed by Vennari et al., 2014), and (iii) three consecutive, non-overlapping 30-year periods (1921–1950, 1951–1980, 1981–2010).

Figure 4 shows the geographical distribution of the total number of REL in each municipality for the four seasons. Most of the REL occurred in winter (728, 49.7 %) and autumn (622, 42.4 %), with only 84 REL (5.7 %) in the spring and 32 REL (2.2 %) in the summer (Table 1). The geographical distribution of the REL occurred in the autumn (Fig. 4a) and winter (Fig. 4b) seasons are similar, with REL in the winter exhibiting average and maximum values of D larger than the REL in the autumn. Conversely, REL in the autumn have (on average) larger values of E (Table 1). Summer REL have typically low D, with a maximum duration of 5 days (Table 1). Figure 4c shows that REL in the spring were most numerous in the NE part of the region.

Figure 5 shows the geographical distribution of the total number of REL in each municipality for the "dry" period from April to October (Fig. 5b) and the "wet" period from November to March (Fig. 5a) adopted by Vennari et al. (2014) to determine seasonal rainfall thresholds for possible landslide occurrence in Calabria. REL in the "dry" period (307, 20.9 %, Table 1) occurred mostly along the E (Ionian) side of the region, whereas REL in the "wet" period (1159, 79.1 %) were distributed throughout the region, with longer rainfall duration D and lower cumulated event rainfall E. Figure 5c and d portray the temporal distribution of the REL in the "dry" and the "wet" periods. The temporal distribution of REL in the "wet" period is similar to the distribution of all the REL (Fig. 2e), whereas in the "dry" period REL were most frequent in the 1950's, and have decreased constantly since then.

Figure 6a, b and c show the number of REL per municipality in three periods: 1921–1950 (old period), 1951–1980 (intermediate period), and 1981–2010 (recent period). Of the 1466 REL in the catalogue, 143 REL (9.8 %) occurred in the old period, 720 (49.1 %) in the intermediate period, and 603 (41.1 %) in the recent period (Table 1). The spatial distributions of the REL in the intermediate and the recent periods are similar, with a larger number of REL affecting the SE part of the region in the recent period. Figure 6d, e and f portray the monthly distributions of the REL in the three periods. In the old period (Fig. 6d) REL occurred between October and March, with the majority of the REL (51, 35.7 %) in November. In the intermediate and the recent periods, the REL were also most abundant between October and March. In particular, in the intermediate period 1951–1980, REL were equally distributed in the autumn (322, 44.7 %) and the winter (329, 45.7 %), with peaks in October (145, 20.1 %) and November (170, 11.6 %, Fig. 6e). In the recent period, the majority of the REL (369, 61 %) occurred in winter, with a distinct peak in January (162 REL, 26.9 %) (Fig. 6f) and only 86 REL (14.3 %) in October and November. In the three considered periods, the REL exhibited similar ranges of rainfall duration D, and different ranges of cumulated event rainfall E (Table 1), with the REL in the recent period exhibiting larger maximum D, and lower average and maximum E than the corresponding values for the REL in the previous periods.

7 Discussion

Using the three catalogues of landslide events (LE), of rainfall events (RE), and of rainfall events with landslides (REL) in Calabria in the 90-year period 1921–2010, we first investigate the changes in the yearly distribution of rainfall events with landslides. This is followed by an analysis of the changes in the rainfall conditions that have resulted in landslides in Calabria, measured by empirical rainfall thresholds for landslide occurrence. Lastly, we compare the variations in the number and distribution in time of landslide events with the variations in the density of the population in each municipality in Calabria, to analyse variations in the landslide impact and risk to the population.

Three key aspects of our analyses need to be addressed. First, our catalogues consider only rainfall-induced landslides that were noticed (and recorded) because they have caused damage to public or private properties, or to the population. Thus, the catalogues, and particularly the landslide catalogue, are not complete. Second, an underestimation in the number of landslides in the old period of the series (1921–1950) is expected, due to the reduced availability of the sources of information. For this reason, we conduct our most relevant analyses comparing the intermediate (1951–1980) and the recent (1981–2010) periods, which we consider equally complete for statistical purposes (Fig. 6). Third, the daily time scale of the rainfall series used for our analysis is not sufficient to determine rainfall thresholds for short duration (< 24 h) events. Thus, the thresholds defined in this work are not adequate for rainfall durations < 24 h, and cannot be used in landslide warning systems. However, we maintain that the thresholds are adequate to analyse variations in the landslide rainfall triggering conditions in Calabria.

7.1 Changes in the yearly distribution of REL

To determine if the yearly distribution of REL has changed in the 90-year observation period, we analysed the histograms shown in Fig. 6d, e, and f, and we computed for each month the ratio REL_i / REL_j, with $i =$ (January, February, ..., December) and $j =$ (January, February, ..., December), for the three 30-year periods (see Supplement). Among all the possible combinations, we found that the ratio between the number of REL in January (REL_{Jan}) and in November (REL_{Nov}) i.e., REL_{Jan} / REL_{Nov}, is the best indicator of the variation in the occurrence of REL in the studied period. The ratio was very low (0.61) in the old period, it increased slightly (0.85, +28.2 %) in the intermediate period, and it increased significantly (4.76, +82.1 %) in the recent period. The distribution of the RE is similar in the three periods, with largest values between September and March (Fig. 6g, h and i). The ratio RE_{Jan} / RE_{Nov} was 1.02 in the old period; it increased to 1.14 (+11.8 %) in the intermediate period, and increased further to 1.23 (+7.9 %) in the recent period. Table 2 lists the average and maximum values of the cumulated event rainfall E (in mm) for rainfall events reconstructed in the entire 90-year period, and in the three considered 30-year periods. RE occurred in October and November in the intermediate period have larger (average, maximum) cumulated event rainfall E than RE occurred in the same 2 months in the recent period (Table 2). Conversely, REL occurred in December and January exhibit similar values of E (average, maximum) for all the three periods. Despite the fact that the monthly number and ratios of RE did not change significantly in the three 30-year periods, the number of REL and their distribution

Table 2. Average (mean) and maximum (max) values of cumulated event rainfall E (in mm) for rainfall events in the 90-year period 1921–2010, and in three 30-year periods. The largest monthly values in each period are shown in bold.

Month	1921–2010		1921–1950		1951–1980		1981–2010	
	mean	max	mean	max	mean	max	mean	max
January	170.7	999.9	169.3	985.8	168.1	758.9	**174.7**	**999.9**
February	160.8	959.5	155.5	753.9	**163.2**	**959.5**	163.6	771.8
March	164.5	1118.3	**181.6**	**1118.3**	149.3	806.1	162.7	656.2
April	145.2	**1124.4**	137.8	298.7	**149.0**	**1124.4**	148.9	355.7
May	148.6	811.8	138.5	351.2	142.6	452.6	**164.6**	**811.8**
June	163.9	813.0	136.5	331.0	143.2	741.2	**212.1**	**813.0**
July	163.7	403.4	134.2	314.8	133.8	266.7	**223.0**	**403.4**
August	130.3	257.4	133.6	255.9	121.8	239.7	**135.4**	**257.4**
September	165.4	748.4	159.8	470.5	143.0	425.0	**193.3**	**748.4**
October	170.2	1504.7	158.3	533.5	**198.6**	**1504.7**	153.7	528.6
November	174.6	872.0	169.8	734.0	**194.2**	**872.0**	159.7	477.4
December	**175.0**	1250.7	**181.6**	1216.2	174.8	**1250.7**	168.6	696.0

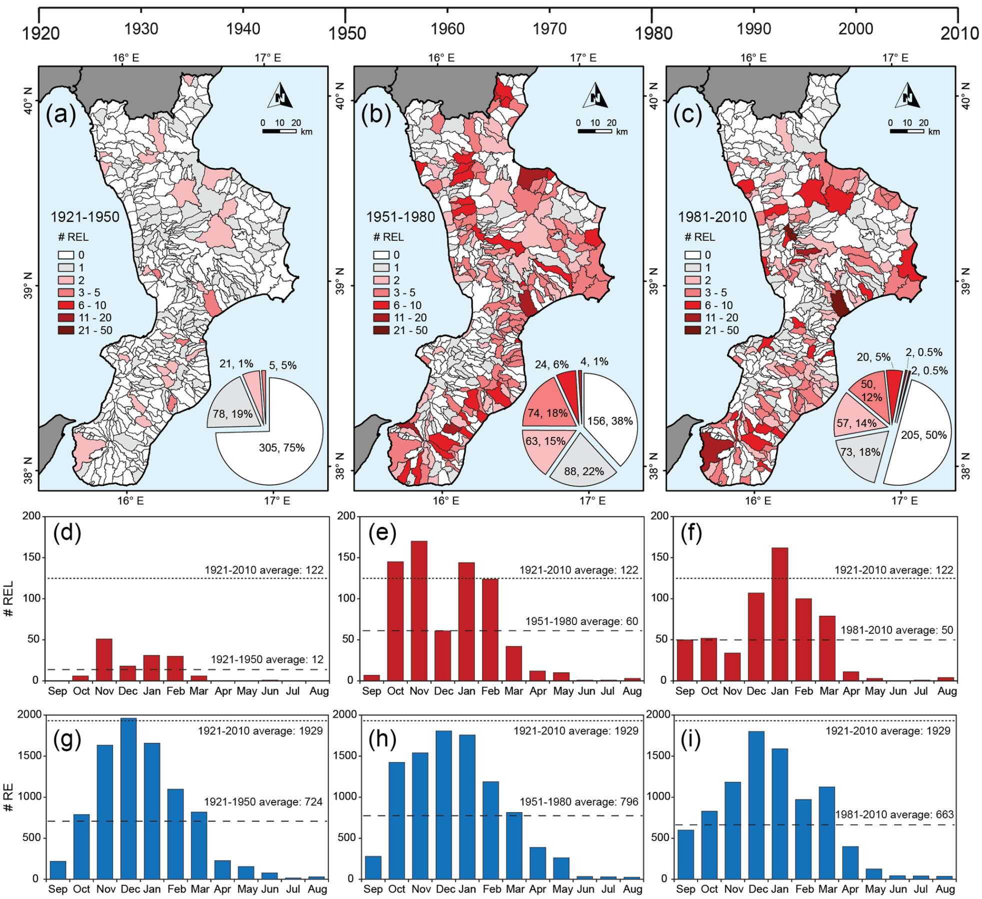

Figure 6. Maps show the number of rainfall events with landslides (#REL) in each municipality in Calabria in the three 30-year periods, **(a)** 1921–1950, **(b)** 1951–1980, and **(c)** 1981–2010. Pie charts show number and percentage of municipalities in each class. Middle: Red bars in **(d)**, **(e)** and **(f)** show number of REL per month in the three 30-year periods. Bottom: Blue bars in **(g)**, **(h)** and **(k)** show number of RE per month in the three 30-year periods.

through the year changed significantly, outlining a variation in the distribution of REL in the three 30-year periods.

7.2 Changes in the rainfall thresholds

To ascertain whether the rainfall conditions for possible landslide occurrence have changed in Calabria in the 90-year observation period, we defined cumulated event rainfall–rainfall duration (ED) thresholds for all the REL in the catalogue, and for different subsets. Table 3 lists the equations and the ranges of validity of the established 5 % ED thresholds. Except for the validity range, only minor differences exists in the parameters controlling the thresholds defined for the entire catalogue ($T_{5,\mathrm{CAL}}$), for rainfall conditions that have resulted in "single" ($T_{5,\mathrm{SG}}$) or "multiple" ($T_{5,\mathrm{ML}}$) landslides, and for rainfall conditions that have caused "small" ($T_{5,\mathrm{SL}}$) or "large" ($T_{5,\mathrm{LG}}$) landslides.

Inspection of Table 3 reveals that the $T_{5,\mathrm{CAL}}$, $T_{5,\mathrm{SG}}$ and $T_{5,\mathrm{ML}}$ thresholds have the same or very similar exponent (γ) and intercept (α) of the power law models. Although the average and the maximum cumulated event rainfall E responsible for "single" landslides are smaller than the E that have resulted in "multiple" landslides, the rainfall amount required to trigger "single" or "multiple" landslides has remained the same in Calabria in the 90-year observation period. The same is true for the rainfall conditions that have resulted in "small" or "large" landslides (Table 3). However, rainfall events that have resulted in "small" landslides have maximum and average rainfall duration D and cumulated event rainfall E lower than the rainfall events that have resulted in large landslides (Table 1).

Considering the seasonal periods, the threshold defined for autumn ($T_{5,\mathrm{AT}}$, $\gamma = 0.82 \pm 0.04$) is steeper than the threshold defined for winter ($T_{5,\mathrm{WT}}$, $\gamma = 0.74 \pm 0.04$), and the threshold for the "wet" period ($T_{5,\mathrm{WET}}$, $\gamma = 0.75 \pm 0.03$) is flatter than the threshold for the "dry" period ($T_{5,\mathrm{DRY}}$, $\gamma = 0.99 \pm 0.04$). For the latter two thresholds the intercepts (α) are also different (Table 3). The number of the empirical data for the spring and the summer periods was not sufficient to determine reliable thresholds (Vennari et al., 2014), and a comparison for the two seasons is not possible.

Figure 7a compares the ED threshold defined in this work for Calabria ($T_{5,\mathrm{CAL}}$) to the threshold defined by Vennari et al. (2014) ($T_{5,\mathrm{VEN}}$) for shallow landslides using rainfall and landslide information in the period 1996–2011. The $T_{5,\mathrm{CAL}}$ threshold is significantly steeper than the $T_{5,\mathrm{VEN}}$ threshold ($\gamma = 0.74 \pm 0.03$ vs. $\gamma = 0.41 \pm 0.03$), and can be applied only for $D > 24$ h ($24 \leq D \leq 768$ h), whereas the $T_{5,\mathrm{VEN}}$ is applicable for $1 \leq D \leq 451$ h. We maintain that the observed difference depends largely on the different resolution of the rainfall records i.e., daily measurements for our catalogue and hourly measurements for Vennari et al. (2014).

Figure 7b shows that the ED thresholds for landslide occurrence in Calabria are different for the three 30-year considered periods ($T_{5,21-50}$, $T_{5,51-80}$, $T_{5,81-10}$). Inspection of Table 1 confirms that the three thresholds are different, both for their intercepts (α) and the slopes (γ). However, considering the uncertainty associated to the thresholds (Brunetti et al., 2010; Peruccacci et al., 2012), we observe that the thresholds overlap for $40 < D < 400$ h. We further observe that $T_{5,21-50}$ is the steepest threshold ($\gamma = 0.93 \pm 0.05$) and $T_{5,81-10}$ is the less steep threshold ($\gamma = 0.66 \pm 0.04$). We infer that for rainfall events having $D \leq 72$ h (3 days), less rain was required to trigger landslides in the old (1921–1950) period than in the intermediate and in the recent periods.

7.3 Changes in the landslide impact to the population

To investigate the variations in the impact of landslides on the population of Calabria, we compared the number of REL with the size of the population in each of the 409 municipalities in the region. For the purpose, we used population data available from national Censuses conducted by the Italian National Institute of Statistics (ISTAT – www.istat.it) in 1951 (1 995 084 people in Calabria), 1981 (2 061 182), and 2011 (1 958 923). For simplicity, we attributed the population in 1951, 1981 and 2011 to the entire old, intermediate, and recent periods, without performing any interpolation or demographic modelling.

Figure 8a, b, c portray the changes in the density of the population in the 409 municipalities, for the three considered periods. The number of municipalities with a low (≤ 100 inhabitants per km^2) or medium (101–200 inhabitants per km^2) population density decreased in the 90-year observation period. This was matched by an increase in the number of urbanised municipalities (> 500 inhabitants per km^2), which have increased from 11 (2.7 %) in the old period, to 12 (2.9 %) in the intermediate period, to 18 (4.4 %) in the recent period. The number of municipalities with a very low population density (< 50 inhabitant per km^2), located primarily in mountain areas (Fig. 1a), increased significantly, from 45 (11 %) in the old period, to 75 (18 %) in the intermediate period, to 118 (29 %) in the recent period (Fig. 8a, b, c). This is evidence of an uneven redistribution of the population in Calabria in the observation period. The number of municipalities with a population density in the range 200–500 inhabitants per km^2 has remained about constant, throughout the investigated period.

To evaluate the impact of REL on the population, we adopt two strategies. The first strategy considers impact as $I_{\mathrm{REL}} = \#\mathrm{REL} / P$, where #REL is the total number of REL in a period, and P is a measure of the size of the population in the same period and geographical area. This is similar to determining landslide mortality, where mortality is the number of landslide fatalities (deaths and missing persons) in a population, scaled to the size of the population (Guzzetti et al., 2005b). The second strategy considers impact as $R_{\mathrm{REL}} = \#\mathrm{REL} \times P$ where again #REL is the total number of REL in a period, and P the size of the population in the same period and geographical area. This is equiv-

Table 3. Cumulated event rainfall-rainfall duration (ED) thresholds, at 5 % exceedance probability, for rainfall-induced landslides in Calabria, for the entire catalogue and for different subsets. #REL is the number of rainfall events used to define the threshold.

Data set	#REL	Validity range (h)	Threshold equation
Entire catalogue	1466	$24 \leq D \leq 768$	$T_{5\text{CAL}}: E = (1.6 \pm 0.2) \cdot D^{(0.74 \pm 0.03)}$
Single landslides	534	$24 \leq D \leq 768$	$T_{5,\text{SG}}: E = (1.3 \pm 0.3) \cdot D^{(0.75 \pm 0.04)}$
Multiple landslides	932	$24 \leq D \leq 576$	$T_{5,\text{ML}}: E = (1.4 \pm 0.2) \cdot D^{(0.74 \pm 0.03)}$
Small landslides	610	$24 \leq D \leq 672$	$T_{5,\text{SL}}: E = (1.8 \pm 0.4) \cdot D^{(0.69 \pm 0.04)}$
Large landslides	314	$24 \leq D \leq 768$	$T_{5,\text{LG}}: E = (1.5 \pm 0.4) \cdot D^{(0.72 \pm 0.04)}$
Winter	728	$24 \leq D \leq 768$	$T_{5,\text{WT}}: E = (1.4 \pm 0.3) \cdot D^{(0.74 \pm 0.04)}$
Spring	84[a]	$24 \leq D \leq 456$	n.a.
Summer	32[a]	$24 \leq D \leq 120$	n.a.
Autumn	622	$24 \leq D \leq 672$	$T_{5,\text{AT}}: E = (1.1 \pm 0.3) \cdot D^{(0.82 \pm 0.04)}$
Wet period (Nov–Mar)	1159	$24 \leq \text{D} \leq 768$	$\text{T}_{5,\text{WET}}: E = (1.4 \pm 0.2) \cdot D^{(0.75 \pm 0.03)}$
Dry period (Apr–Oct)	307	$24 \leq D \leq 456$	$T_{5,\text{DRY}}: E = (0.5 \pm 0.2) \cdot D^{(0.99 \pm 0.04)}$
1921–1950	143	$24 \leq D \leq 672$	$T_{5,21-50}: E = (0.6 \pm 0.2) \cdot D^{(0.93 \pm 0.05)}$
1951–1980	720	$24 \leq D \leq 576$	$T_{5,51-80}: E = (1.4 \pm 0.3) \cdot D^{(0.75 \pm 0.04)}$
1981–2010	603	$24 \leq D \leq 768$	$T_{5,81-10}: E = (2.0 \pm 0.4) \cdot D^{(0.66 \pm 0.04)}$
Vennari et al. (2014)	186	$1 \leq D \leq 451$	$T_{5,\text{VEN}}: E = (8.6 \pm 1.1) \cdot D^{(0.41 \pm 0.03)}$

* Number of REL insufficient to determine a reliable threshold. See Vennari et al. (2014).

alent to determining landslide risk using a simplified version of the well-known equation $R = H \times V \times E$ (Varnes et al., 1984; Carrara et al., 1991), where R is landslide risk, H is landslide hazard, V is vulnerability to landslides, and E represents the exposed elements. For our simplified assessment we take $H = \#\text{REL}$, vulnerability $V = 1$, and exposure $E = P$.

Adopting the first strategy, we calculated I_{REL} in Calabria for the three considered periods. We found that I_{REL} was 7.2×10^{-5} in the old period 1921–1950, it increased significantly to 3.5×10^{-4} (+79 %) in the intermediate period 1951–1980, and decreased slightly to 3.1×10^{-4} (−13 %) in the recent period 1981–2011. We conclude that, overall, I_{REL} has increased in Calabria in the entire observation period. This is because the number of the rainfall events with landslides has changed more significantly than the size of the population.

Population did not change (increased/decreased) evenly in Calabria in the investigation period (Fig. 8a, b, c). For this reason, we computed the ratio between the number of REL and the number of people in each municipality, for the three considered 30-year periods (Fig. 8d, e, f). In the old period (1921–1950), 75 % of the municipalities (305 out of 409, Fig. 8d) did not experience REL ($I_{\text{REL}} = 0$), based on the information listed in our catalogue. The percentage decreased significantly to 38 % (156 municipalities) in the intermediate period (1951–1980, Fig. 8e), and increased again to 50 % (205 municipalities) in the recent period (1981–2010, Fig. 8f). The percentage of the municipalities with more than 1 REL per 1000 inhabitants went from 1 % (three municipalities) in the old period, to 25 % (100) in the intermediate period, to 19 % (80) in the recent period. In the intermediate period, large values of I_{REL} were distributed throughout the region, whereas in the recent period they have been more abundant in the S part of the region (Fig. 8e and f). In the recent period, five out of six municipalities with more than five REL per 1000 inhabitants were located in the southernmost tip of the region, outlining an area with a high concentration of events and few inhabitants. In the 1921–1950 period, the maximum value of I_{REL} was 1.5 (orange in Fig. 8d). Then it exceeded 5.0 in the intermediate and the recent periods (red in Fig. 8e and f). In the last two periods, I_{REL} was highest in the municipality of Plataci, in the northern part of the region, reaching 9.7 in the intermediate period (1951–1980) and decreasing to 7.2 in the recent period (1981–2010).

Using the second strategy, we calculated R_{REL} for all the municipalities in Calabria, for the three 30-year periods. We found that R_{REL} was 2.9×10^8 in the old period 1921–1950, increased markedly to 1.5×10^9 (+81 %) in the intermediate period 1951–1980, and decreased slightly to 1.2×10^9 (−26 %) in the recent period 1981–2011. We conclude that, overall, R_{REL} has also increased in Calabria in the entire observation period. Figure 8g, h, i portray three maps showing the 409 municipalities classified based on R_{REL}, in four classes i.e., null ($R_{\text{REL}} = 0$), low ($0 < R_{\text{REL}} \leq 10\,000$), medium ($10\,000 < R_{\text{REL}} \leq 100\,000$), and high ($R_{\text{REL}} > 100\,000$). The number of municipalities characterised by high R_{REL} (high risk of REL) went from 2 (Catanzaro and Reggio Calabria) in the 1921–1950 period, to 6 in the 1951–1980 period, to 10 in the 1981–2010 period. Comparing the intermediate and the recent period, the number of municipalities with medium risk of REL decreased from 79 (19 %) to 50 (12 %). In this latter period,

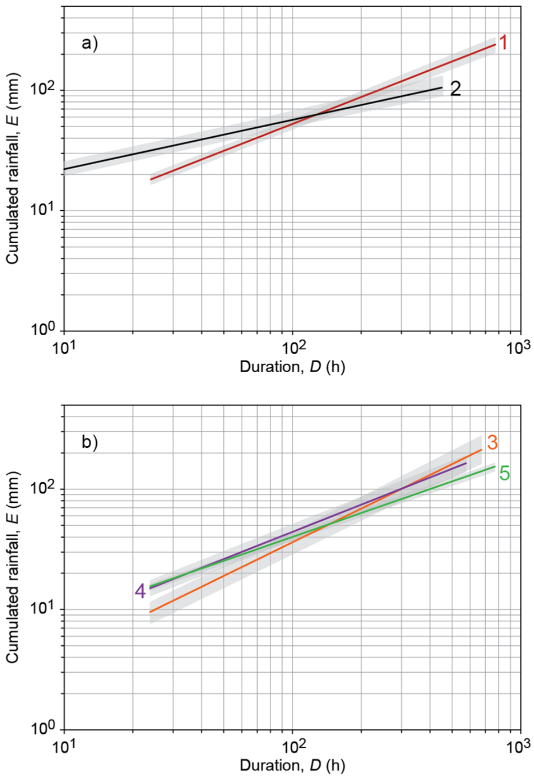

Figure 7. (a) Cumulated event rainfall–rainfall duration (ED) 5 % thresholds for rainfall-induced landslides in Calabria defined in this study ($T_{5,\mathrm{Cal}}$, 1), compared to the 5 % threshold for shallow landslides in Calabria defined in Vennari et al. (2014) ($T_{5,\mathrm{Ven}}$, 2). **(b)** Cumulated event rainfall–rainfall duration (ED) 5 % thresholds defined for the three 30-year periods 1921–1950 ($T_{5,21-50}$, 3), 1951–1980 ($T_{5,51-80}$, 4), and 1951–2010 ($T_{5,81-10}$, 5). Grey areas show uncertainties associated to the thresholds. Data shown in log-log coordinates.

municipalities with medium and high risk were located in the E and in the S parts of the region.

I_{REL} and R_{REL} provide different and complementary information of the impact of landslides to the population of Calabria, and its temporal and geographical variations. We have attempted to combine this information in a single map, shown in Fig. 9. Considering the changes in the number of REL and the number of inhabitants in each municipality between the intermediate (1951–1980) and the recent (1981–2010) period (i.e., the periods for which our catalogues are considered complete for statistical purposes), four cases exist. The first case consists of 73 (18 %) municipalities (red areas in Fig. 9, covering 2336 km^2, 15.5 % of the region) where the number of REL has increased (from 102 to 288, +65 %) and the size of the population has decreased (from a total of 455 054 to 362 470 inhabitants, −26 %) in the recent period, compared to the previous (intermediate) period. In these municipalities a reduced (smaller) number of people has suffered a larger number of rainfall events with landslides. We conclude that I_{REL} has increased in these 73 municipalities, of which 33 municipalities increased the impact from $I_{\mathrm{REL}} = 0$ (no REL recorded in the catalogue) in the intermediate period to $I_{\mathrm{REL}} > 0$ in the recent period. In 69 of the 73 municipalities (95 %) R_{REL} has also increased.

The second case consists of 30 (7 %) municipalities (orange areas in Fig. 9, covering 1008 km^2, 6.7 %) where the number of REL (from 38 to 113, +78 %) and the size of the population (from 432 302 to 470 636 inhabitants, +8 %) have increased in the recent period compared to the previous period. In these 30 municipalities, a larger number of people experienced a larger number of REL i.e., a larger hazard. We conclude that R_{REL} has increased in these 30 municipalities, of which 11 went from $R_{\mathrm{REL}} = 0$ (no REL in the catalogue) to $R_{\mathrm{REL}} > 0$. In 29 out of these municipalities (97 %), I_{REL} has also increased.

The third case consists of 147 (36 %) municipalities (yellow areas in Fig. 9, 5886 km^2, 39.0 %) where the number of REL (from 423 to 138, −207 %) and the size of the population (from 455 822 to 373 889, −22 %) have decreased. In these municipalities a reduced population has suffered a smaller number of REL. We conclude that R_{REL} has decreased in these 147 municipalities, becoming null (no REL in the catalogue) in 75 municipalities (51 %). In 117 of the 147 municipalities (80 %), I_{REL} has also decreased. The fourth case consists of 47 (12 %) municipalities (green areas in Fig. 9, covering 1608 km^2, 10.7 %) where the size of the population has increased (from 325 117 to 407 863, +20 %) and the number of REL has decreased (from 143 to 49, −192 %) in the recent period, compared to the previous period. In these municipalities a larger population has suffered a smaller number of REL. We conclude that I_{REL} has decreased in these 47 municipalities, becoming null (no REL in the catalogue) in 18 municipalities (38 %). In 36 municipalities (77 %) R_{REL} has also decreased.

For 87 % of the municipalities where I_{REL} increased (decreased), R_{REL} also increased (decreased). This was expected, as I_{REL} and R_{REL} depends on the same parameters. However, the fact that local differences exist in the temporal patterns of I_{REL} and R_{REL} reveals that the two indexes measure different properties of the impact of REL to the population, in Calabria. In 112 municipalities (27.4 %) (white areas in Fig. 9, covering 4242 km^2 of the region, 28.1 %), no variation in R_{REL} and I_{REL} between the intermediate and the recent period was observed (no REL in the catalogue in both periods).

Overall, I_{REL} has increased in 73 municipalities and decreased in 47 municipalities, covering 15.5 % and 10.7 % of the region, respectively. The 73 municipalities where I_{REL} has increased host 18.5 % of the population of Calabria, and the 47 municipalities where I_{REL} has decreased host 20.8 % of the population. R_{REL} has increased in 30 municipalities, covering 6.7 % of the region and with 24.0 % of the total population. Conversely, R_{REL} has decreased in 147 municipalities, covering 39.0 % of the region and with 19.1 % of the

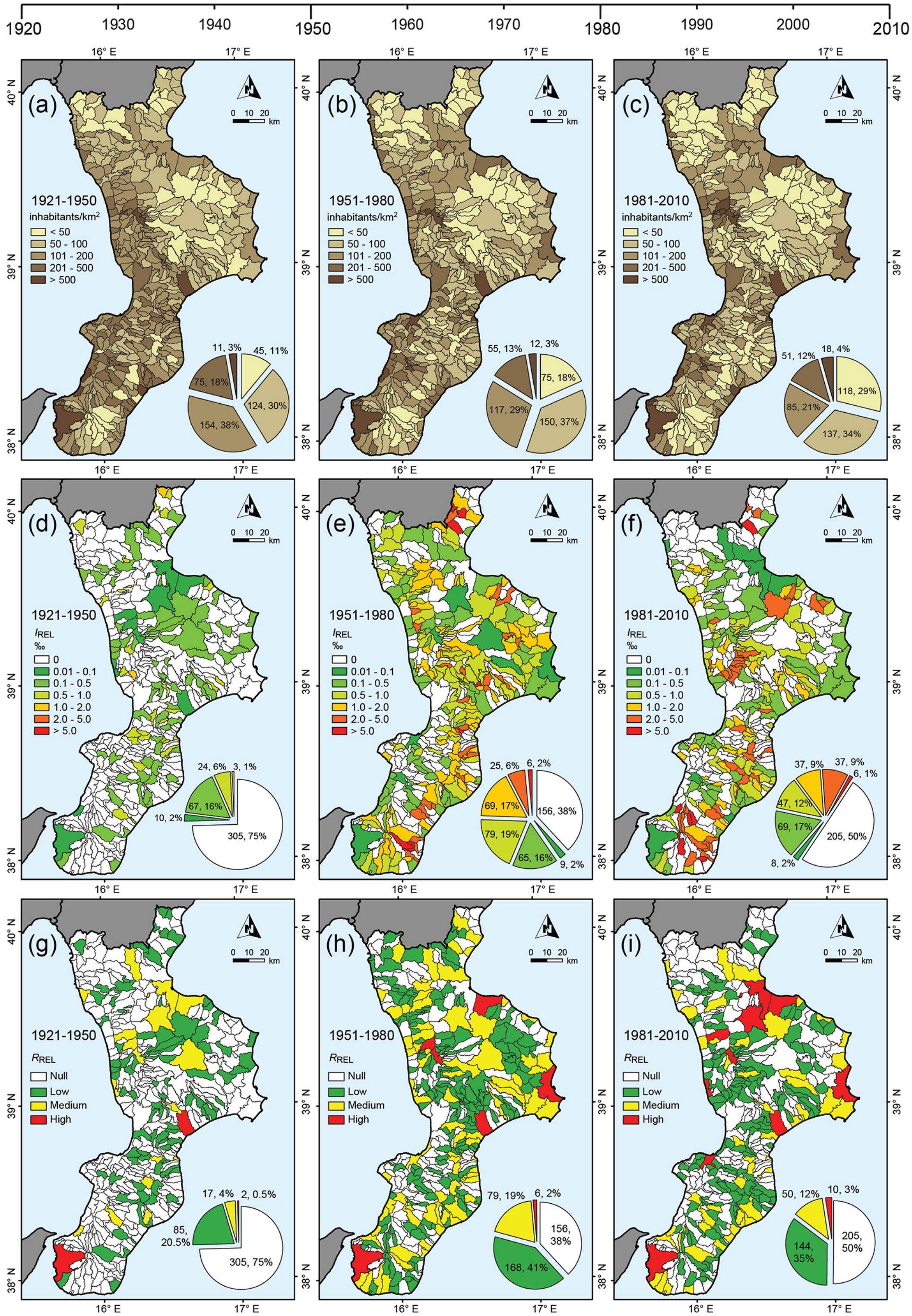

Figure 8. Top: Maps show density of population in the 409 municipalities in Calabria for three 30-year periods, **(a)** 1921–1950, **(b)** 1951–1980, and **(c)** 1981–2010. Middle: Maps show landslide impact I_{REL} given by the number of rainfall events with landslides (#REL) per 1000 people in each municipality in Calabria, for the **(d)** 1921–1950, **(e)** 1951–1980, and **(f)** 1981–2010 periods. Bottom: Maps show risk of rainfall events with landslides R_{REL}, given by the product of the number of rainfall events with landslides (#REL) and of inhabitants in each municipality in Calabria, for the **(g)** 1921–1950, **(h)** 1951–1980, and **(i)** 1981–2010 periods. Key: Null, $R_{\mathrm{REL}} = 0$; Low, $0 < R_{\mathrm{REL}} \leq 10\,000$; Medium, $10\,000 < R_{\mathrm{REL}} \leq 100\,000$; High, $R_{\mathrm{REL}} > 100\,000$. Pie charts show number and percentage of municipalities in each class.

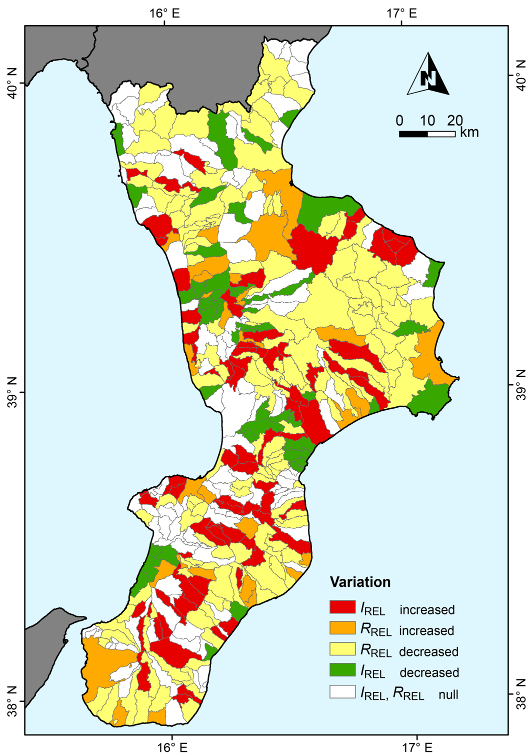

Figure 9. Map showing variations in I_{REL} and R_{REL} in the municipalities of Calabria, between the intermediate (1951–1980) and the recent (1981–2010) periods. Legend: Red, municipalities with an increased I_{REL} (increased number of REL and a smaller population). Orange, municipalities with an increased R_{REL} (increased number of REL and a larger population). Yellow, municipalities with a decreased R_{REL} (decreased number of REL and a smaller population). Green, municipalities with a decreased I_{REL} (decreased number of REL and a larger population). White, municipalities with I_{REL} and R_{REL} null (no REL listed in the catalogue in the intermediate and in the recent periods).

population. Overall, 93 municipalities went from $R_{\mathrm{REL}} > 0$ and $I_{\mathrm{REL}} > 0$ in the intermediate period, to $R_{\mathrm{REL}} = 0$ and $I_{\mathrm{REL}} = 0$ in the recent period. In these municipalities the risk of REL to the population has decreased. Conversely, 44 municipalities changed from $R_{\mathrm{REL}} = 0$ and $I_{\mathrm{REL}} = 0$ in the intermediate period, to $R_{\mathrm{REL}} > 0$ and $I_{\mathrm{REL}} > 0$ in the recent period. In total, 42.5 % of the regional population suffered an increased impact, both in terms of I_{REL} and R_{REL}. Municipalities where I_{REL} has increased between the intermediate and the recent period are located mainly in the inner and mountainous areas of the region, and municipalities where I_{REL} has decreased between the two periods are mostly along the coasts and in the N part of the region. Municipalities where R_{REL} has increased in the recent period, compared to the intermediate period, are located mainly along the coasts, and the municipalities where R_{REL} are unevenly distributed in the entire regional.

We recognise that multiple factors have conditioned the results of our analyses and the discussion. These include (i) the completeness of the landslide catalogue, (ii) the reliability and homogeneity of the rainfall records, (iii) the length (90 years) of the catalogue, (iv) the number (3) and length (30 years) of the segmentation periods of the catalogue, (v) the modelling tools and parameters used to single out the RE and the REL, and (vi) to determine the rainfall thresholds. More sophisticated statistical techniques may also be used to analyse the catalogues of landslide events, of rainfall events, and of rainfall events with landslides (Rossi et al., 2010; Witt et al., 2010). For these reasons, we acknowledge that our results are preliminary.

8 Conclusions

We have investigated geographical and temporal changes in the occurrence of 1466 rainfall-induced landslide events in Calabria, in the 90-year period 1921–2010.

Our work revealed that the rainfall conditions that have resulted in rainfall-induced landslides in Calabria have changed in the observation period. We found that less cumulated event rainfall (E) was necessary to trigger landslides in the recent period (1981–2010) than in the preceding period (1951–1980). We consider this evidence of the increased propensity of the landscape to generate landslides in the recent period, and of the larger number of vulnerable elements exposed to landslides, in Calabria. We found that the monthly distribution of rainfall events with landslides (REL) has changed. In the earlier period (1951–1980) landslides were more frequent in autumn and winter, whereas in the recent period (1981–2010) landslides concentrated in the winter. We further observed significant variations in the geographical distribution of the REL. In the recent period (1981–2010) REL struck mainly the SE part of the region. We attribute the observed variations in the temporal and the geographical distributions of rainfall events with landslides in Calabria to variations in the frequency of the triggering rainfall events, and to an increased susceptibility to landslide of the territory.

We investigated the changes in the influence of rainfall events with landslides on the population of Calabria, adopting two complementary strategies. The analysis revealed a complex picture. The impact of REL on the population has increased in 37 municipalities covering 15.5 % of the total area and hosting 18.5 % of the population, and has decreased in 47 municipalities covering 17.8 % of the total area and hosting 20.8 % of the population. The risk posed by REL to the population has increased in 30 municipalities covering 6.7 % of the total area and hosting 24.0 % of the population, and has decreased in 47 municipalities covering 39.0 % of the total area and hosting 19.1 % of the population. Overall, 42.5 % (57.5) of the regional population has experienced an increased (decreased) level of landslide impact or risk.

We note that the observed changes in the impact of rainfall-induced landslides on the population of Calabria in the investigated 90-year period are due to changes in the number of the events (a largely natural component) and to changes in the number of the exposed elements (a largely societal component). Several of the municipalities with an increased landslide risk between the intermediate and the recent periods have experienced a similar number of REL (hazard has remained about the same) in the two periods, but a large increase in the size of the population (exposure has increased) in the recent period.

Overall, our research revealed a complex picture of the changes in the impact of rainfall-induced landslides in Calabria in the recent past, with areas where the impact and risk to the population have increased, and other areas where the impact and risk have decreased. The geographical pattern of the variations is diversified (Fig. 9), revealing the complexity of the interactions between the natural (climate) and the human induced (population, land cover) factors that control the frequency of the rainfall-induced landslides, and the intensity of the consequences. We argue that there was nothing special or peculiar in the natural and societal landscapes in Calabria. We therefore hypothesise that the same complexity and variability exists in similar surrounding regions, in Italy and in the Mediterranean region. The hypothesis can be tested using the same methodology experimented in this paper for the joint analysis of historical landslide, rainfall and population information, anywhere adequate information is available.

Finally, we stress that the complexity of the temporal and geographical pattern of the variations in the frequency and impact of rainfall-induced landslides observed for the recent past in Calabria suggests that it will be difficult and uncertain to predict the possible variations in the frequency and impact in response to future climatic and environmental changes.

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