Brief communication: A century of landslide records in Calabria, southern Italy, looking for changes and trends through a dynamic analysis

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Abstract. This study updates an article published in NHESS journal in 2015 and investigates long-term changes in landslide-triggering rainfall conditions in Calabria (southern Italy) over 1921–2020. A catalogue of 3006 rainfall events associated with landslides (RELs) was reconstructed using 9530 landslide records and daily rainfall measurements from 318 gauges. Rainfall thresholds were calculated for 15 30-year moving windows to investigate the triggering conditions of the RELs. Results show a marked increase in the number of RELs after 2009, shifts in seasonal occurrence, and decreasing rainfall duration and cumulative amounts. Triggering rainfall shows an overall decreasing trend over the years.

1 Introduction

The relationships between rainfall and landslide occurrence/activation can be modelled using either a physically based or an empirical/statistical approach. Both approaches can also be employed to assess the role of climate change in the occurrence, frequency, and activity of landslides (Gariano and Rianna, 2025). To this aim, empirical analyses of landslides and rainfall records, usually lasting from 30 to 100 years, attempt at assessing geographical and temporal variations in landslide activity over region- to nation-wide areas.

Historical documentary data represent the principal source of information about landslide occurrences required for implementing empirical models. Documentary data are an ideal source for disasters because they can serve as "tools for detecting and responding to threats" (Kapucu et al., 2023), remaining the main tool for constructing databases of hazardous events such as earthquakes (Simón et al., 2022), floods (Rilo et al., 2022), landslides (Calvello and Pecoraro, 2018; Peruccacci et al., 2023), and drought (van der Schrier et al., 2021). The digitization of old archives and the availability of online sources for more recent periods have enabled the creation of numerous data catalogues, and even georeferenced databases, covering very long periods of impact caused by floods, landslides, and mixed phenomena on specific elements, such as for example, transport networks (Petrucci et al., 2025) or specific municipal territory (Conforti et al., 2025). However, non-instrumental records derived from documentary sources may suffer from incompleteness, which can be challenging to quantify.

In a paper published in *Natural Hazards and Earth System Sciences* in 2015, an empirical analysis of the spatial and temporal changes of rainfall-triggered landslides in Calabria, southern Italy, covering the 90-year interval from 1921 to 2010, was conducted by Gariano et al. (2015). Information of 7000+ landslides and daily rainfall measurements were used to reconstruct 1466 *rainfall events with landslides* (RELs), defined as the recording of one or more landslides during or after a rainfall event. Three 30-year subperiods (1921–1950, 1951–1980, and 1981–2010) were considered to analyse the changes in the spatial and temporal distribution of the RELs and in the rainfall conditions that caused the landslides. The main temporal change observed was that the RELs were more concentrated in late winter and early spring in the recent period 1981–2010. The landslide-triggering rainfall conditions were evaluated calculating cumulated rainfall-duration thresholds defined using the frequentist method (Brunetti et al., 2010) in each of the three defined 30-year periods. The main finding was that, in the recent-most 30-year period (1981–2010), the average and maximum values of the cumulative rainfall that triggered the landslides were lower than in the previous periods.

That work is now updated with this article by adding ten more years of data (period 2011–2020) and by introducing a methodological novelty. In particular, the analysis of the triggering conditions of the RELs is here carried on over the entire 100-year dataset considering multiple 30-year periods defined using a moving window with a 5-year step, rather than only for the three separated 30-year periods. This dynamic analysis allows for a more precise evaluation of the changes and a better identification of trends.

A similar dynamic approach was used by Peres et al. (2023) to assess projected climate change impacts on drought in southern Italy, using the control period 1971–2000 and the future period 2011–2070. In this work, such dynamical analysis is applied to a very long dataset (100 years) of landslide occurrences, taking advantage of rainfall thresholds, which are well-established tools used to define the triggering conditions of rainfall induced mass-movements, but were also used, with different methodologies, to evaluate past and future changes in landslide triggering conditions (e.g., Sangelantoni et al., 2018; Bezak and Mikoš, 2021).

The data and methods used are described in Sect. 2; Sect. 3 illustrates the results of the analysis, which are discussed in Sect. 4. The main concluding remarks are presented in Sect. 5.

2 Methods and Data

2.1 Methods

As in the previous paper, the analysis is based on the identification of landslide events (LEs), rainfall events (REs), and rainfall events with landslides (RELs). Since the period of analysis goes back a long way, including years in which only daily rainfall was measured, the temporal resolution used in this work, for both landslides and rainfall, is daily. This is the minimum resolution that is available over the entire time interval; in more recent decades, information on landslides has also become increasingly detailed in terms of time; moreover, in the Calabria region, hourly rainfall data are only available since 1990. On the other hand, despite for the new records the precise location, or even the coordinates are available, for the oldest ones only the municipalities of occurrence were known. For this reason, for the sake of uniformity, the municipal boundaries were used as units of analysis. Following Gariano et al. (2015), a LE is defined as the occurrence of a landslide in a given municipality and on a given date (day, month, year); a RE is defined as a continuous sequence of days with cumulated daily rainfall > 0 mm preceded and followed by at least one day with no measured rainfall. Thus, a REL is defined as the occurrence of a LE during (or no more than 1 d after) a RE measured by the closest rain gauge, located within 5 km from the LE location.

The rainfall conditions that triggered the landslides are evaluated by defining the empirical rainfall thresholds with the frequentist method (Brunetti et al., 2010) and the CTRL-T tool (Melillo et al., 2018). According to this method, thresholds are determined by a power law relationship between the rainfall duration D (in hours or days) and the cumulative rainfall E (in mm), according to Eq. (1):

$$E = (\alpha \pm \Delta\alpha) \cdot D^{(\gamma \pm \Delta\gamma)}, \tag{1}$$

where α and γ are the interception and the slope of the curve, and $\Delta\alpha$ and $\Delta\gamma$ are the uncertainties associated with them. With this method, thresholds at different non-exceedance probabilities can be defined; usually, the 5 % non-exceedance probability threshold is calculated.

In this work, the landslide-triggering rainfall thresholds are calculated for 15 30-year periods, defined using a moving window with a 5-year step. This approach allows for a dynamic and more precise evaluation of the changes over the observation period. The threshold calculation is made in this work with the sole purpose of long-term comparative analysis and without aiming to operational landslide prediction.

2.2 Data

The study area is the Calabria region, located in southern Italy with an extension of 15 080 km^2 and characterized by elevations ranging from 0 to 2260 m a.s.l. and mean annual rainfall ranging from less than 600 mm in the coastal plains to more than 1800 mm in the inland mountains (Fig. 1a).

The catalogue of LEs includes information on 9530 LEs recorded in the region from June 1920 to December 2020 (on average 94 LEs yr^{-1}, 8 LEs per month). In the last decade (2011–2020), 1930 additional LEs with a much higher annual frequency (193 LEs yr^{-1}) were added to the catalogue analysed by Gariano et al. (2015). This sharp increase in data collection is likely linked to the greater availability of information sources, such as online newspapers, from which data on landslide occurrences following rainfall events can be obtained for the most recently added period. Despite the higher number of LEs and, more generally, hydro-meteorological events affecting Calabria between 2011 and 2020, it has been observed that the impact on human life in terms of fatalities from landslides and floods during extreme rainfall events has drastically decreased when comparing 2011–2020 for example to the 1950s (Petrucci, 2024). This new analysed period recorded several cases of severe rainfall events affect-

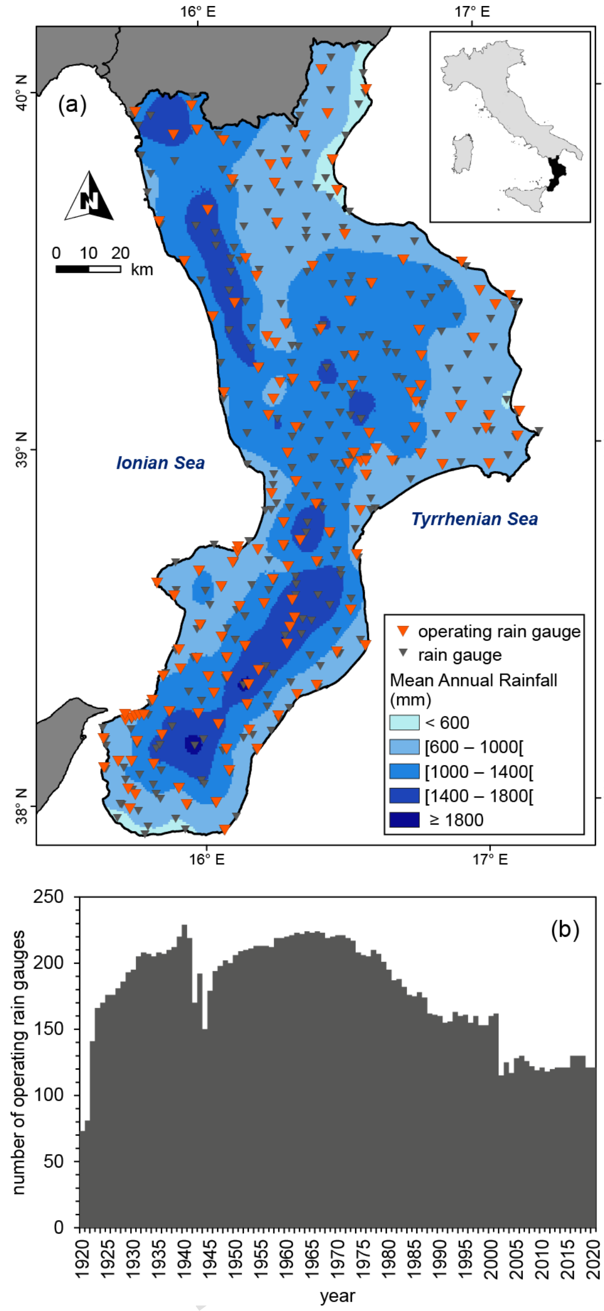

Figure 1. (a) Map of mean annual rainfall in Calabria region, in five classes, and distribution of rain gauges used in this work. **(b)** Number of operating rain gauges per year in Calabria between 1920 and 2020. Updated from Gariano et al. (2015).

ing large parts of the Calabrian territory, causing widespread mass movements, particularly between 2009 and 2012 (e.g., Antronico et al., 2013, 2017; Terranova et al., 2016). Notable examples include the event in August 2015 that struck the northeastern sector of the region (Rago et al., 2021) the November 2015 event that heavily impacted the southernmost areas of the region (Rago et al., 2017). Other significant events occurred at the end of March 2020, and November 2020 (Caloiero et al., 2024) although reports of damage were limited due to restrictions on movement during the Covid-19 pandemic lockdown.

To calculate the REs, we used daily rainfall measurements captured by a network of overall 318 rain gauges across Calabria from 1 January 1921 to 31 December 2020, whose distribution is shown in Fig. 1a. The number of operating rain gauges varied over time with a peak (more than 200 stations) in the 1930s, and between 1950 and 1975 (Fig. 1b). Since 2000, the number of operating stations has settled at around 135. There have been no significant changes in the number and distribution of rain gauges over the recent 10 years (2011–2020) compared to the previous decade (2001–2010). In addition, Fig. 1a shows the map of the mean annual rainfall in the region calculated using rainfall measurements from 1921 to 2020. No relevant variations can be observed with respect to the map produced by Gariano et al. (2015) using data from 1921–2010.

3 Results

3.1 Main features of the RELs

Using the above-described method, 1642 RELs were reconstructed in the period 2011–2020. For 288 LEs it was not possible to associate a RE, for different reasons: the landslides may be not triggered by rainfall, or the rain gauges failed to measure the rainfall. Moreover, following Gariano et al. (2015), the REs with mean rainfall intensity $< 10\,\mathrm{mm\,d^{-1}}$ were discarded from the analysis. This resulted in a further reduction of the number of RELs to 1540. Summing these RELs to the 1466 defined in the previous work for the period 1921–2010, a catalogue of 3006 RELs is obtained and used for the analysis.

The median number of REL in a municipality is 5, the minimum is zero (81 municipalities, located chiefly in the northern part and along the western flank of the region), and the maximum is 143, in the Reggio Calabria metropolitan area. Two other municipalities experienced more than 50 RELs: Catanzaro (97) and Cosenza (64). These three municipalities are the main capital provinces of the region. Overall, in the period investigated, 58 municipalities (14 %) experienced 10 or more REL.

3.2 Temporal distribution of the RELS

Figure 2a portrays the number of RELs per year. On average, 30 RELs occurred every year with a maximum of 288 RELs in 2011 and 260 in 2012.

A considerable increase in the number of RELs starts in 2009, as highlighted by the sharp increase in the cumulative curve in Fig. 2a. As a matter of fact, the last two 30-year moving windows (1986–2015 and 1991–2020) are characterized by more than twice as many events as all the previous ones.

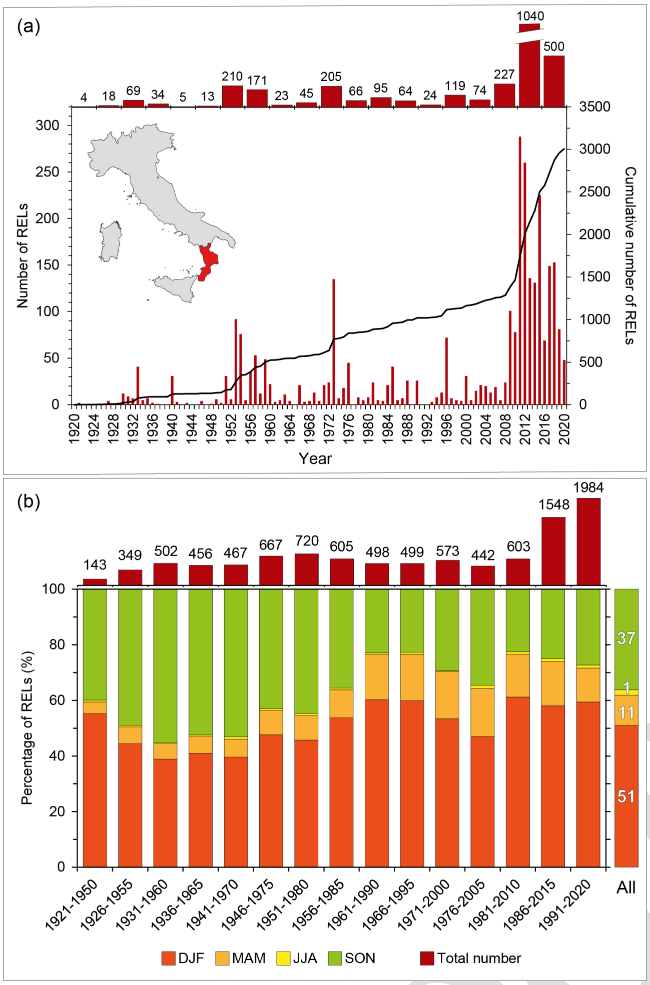

Figure 2. (a) Temporal distribution of Rainfall Events with Landslides (RELs) per year (red bars), and cumulated number of RELs (black line) in the period 1921–2020 in Calabria region (in red in the upeer left inset); the pie chart in the inset shows the seasonal distribution of the RELs; the number of RELs for 5-year intervals is shown in the bars at the top of the graph. **(b)** Seasonal distribution of RELs in the 15 30-year moving windows considered in the study; the total number of RELs in each 30-year period is shown in the bars at the top of the graph. Key: DJF, December–January–February; MAM, March–April–May; JJA, June–July–August; SON, September–October–November.

Over the whole century analysed, RELs occurred mostly in winter and autumn: 51 % of the records in DJF, 37 % in SON, 11 % in MAM, and 1 % in JJA. However, the newly added decade of data has a different seasonal distribution: 44 % in DJF, 34 % in SON, 14 % in MAM, and 7 % in JJA. And indeed, the seasonal distribution changed during the years, as shown in Fig. 2b, which displays these changes across the 15 moving windows considered. A marked increase in the number of RELs recorded in MAM (passing from ∼ 5 % to ∼ 15 % of the annual total), and a pronounced decrease in the number of RELs occurred in SON (from ∼ 45 % to ∼ 25 %) are clearly detectable.

3.3 Triggering conditions of the RELs

Table 1 lists the mean values of D and E of the triggering conditions of the RELs in the 15 30-year periods. The triggering rainfall conditions changed during the observation period. The mean cumulative rainfall decreased over the years, passing from values higher than 200 mm from 1921 to 1980, to values lower than 150 mm in the most recent decades. The duration of the triggering events also shows a decreasing but much less marked trend.

The rainfall thresholds, which represent the minimum, critical triggering conditions of the RELs in the 15 periods, are listed in Table 1 and shown in Fig. 3a. In the figure, the results for only 13 periods are shown, excluding the first two periods, which have a smaller number of empirical points and a lower completeness of the information. It can be observed that the rainfall thresholds were higher in the earlier 30-year periods and have become lower starting from the 1960s and rising again starting from the 1980s. The threshold values for durations of two and four days, which are the time horizons usually adopted for rainfall forecasts, show a decreasing tendency through the whole analysed century (Fig. 3b). Similar decreasing trends can be observed for other durations. This means that the landslide-triggering rainfall events in the study area have become less intense in recent decades compared to the early- and mid-20th century. A finding that may indicate that less rainfall was progressively needed to initiate landslides in the region, i.e. the regional territory has likely become more prone to landslides, over the decades.

4 Discussion

The main methodological innovation introduced in this work is the use of frequentist rainfall thresholds to evaluate the changes in triggering conditions of rainfall-induced landslides over time and their calculation for several 30-year periods defined using a moving window with a 5-year step, rather than only for static sub-periods (as done in the previous work, Gariano et al., 2015). The method is applied to a century of landslide information, resulting in a dynamic analysis that allowed a more precise evaluation of changes and identification of trends that were less detectable with the static analysis. It must be acknowledged that the use of 30-year windows with a 5-year step results in adjacent periods that share 25 years of overlapping data and therefore are not statistically independent. Consequently, minor fluctuations between consecutive windows should not be overinterpreted as independent temporal changes; rather, the focus of this analysis is strictly on the broad, long-term evolutionary trends observed across the entire century.

Table 1. Details of the triggering conditions of the RELs (Rainfall Events with Landslides) and of the ED (cumulative event rainfall–rainfall duration) thresholds at 5 % non-exceedance probability calculated for the 30-year moving periods in the study area. Key: D, rainfall duration (in days); E, cumulative event rainfall (in mm); threshold equations according to Eq. (1) with E in mm and D in days.

Period	REL number	Mean E (mm)	Mean D (days)	D range (days)	Threshold equation	E at 2 d (mm)	E at 4 d (mm)
1921–1950	143	232.1	7.3	1–28	$E = (11.1 + 1.4) \cdot D^{(0.93+0.05)}$	21.1	40.3
1926–1955	349	282.5	6.8	1–28	$E = (12.1 + 1.1) \cdot D^{(0.87+0.04)}$	22.1	40.4
1931–1960	502	253.2	7.9	1–28	$E = (15.5 + 1.3) \cdot D^{(0.77+0.04)}$	26.4	45.1
1936–1965	456	242.9	7.8	1–21	$E = (17.2 + 1.5) \cdot D^{(0.72+0.04)}$	28.3	46.7
1941–1970	467	240.5	7.9	1–24	$E = (15.8 + 1.4) \cdot D^{(0.73+0.04)}$	26.6	44.7
1946–1975	667	236.3	7.5	1–24	$E = (16.1 + 1.4) \cdot D^{(0.73+0.04)}$	26.7	44.3
1951–1980	720	225.7	7.2	1–24	$E = (15.3 + 1.2) \cdot D^{(0.75+0.04)}$	25.7	43.3
1956–1985	605	196.0	7.0	1–27	$E = (15.6 + 1.4) \cdot D^{(0.74+0.04)}$	26.1	43.5
1961–1990	498	182.7	6.4	1–27	$E = (14.1 + 1.4) \cdot D^{(0.76+0.05)}$	23.9	40.4
1966–1995	499	180.9	6.2	1–27	$E = (14.4 + 1.5) \cdot D^{(0.74+0.05)}$	24.1	40.2
1971–2000	573	176.4	5.7	1–27	$E = (13.3 + 0.6) \cdot D^{(0.73+0.00)}$	21.5	34.6
1976–2005	442	145.7	5.4	1–27	$E = (15.2 + 1.4) \cdot D^{(0.66+0.05)}$	24.0	37.9
1981–2010	603	167.2	6.6	1–32	$E = (16.0 + 1.2) \cdot D^{(0.66+0.04)}$	25.3	39.9
1986–2015	1548	134.1	4.6	1–32	$E = (14.3 + 0.6) \cdot D^{(0.72+0.03)}$	23.9	39.3
1991–2020	1984	128.4	4.2	1–32	$E = (13.5 + 0.5) \cdot D^{(0.71+0.02)}$	22.1	36.1

The key finding of the dynamic analysis is a progressive lowering of the severity of the triggering rainfall conditions for the landslides recorded in Calabria over the century 1921–2020, in terms of both average and minimum values (Table 1, Fig. 3a, b), meaning that landslides in the region were initiated by less rainfall in the recent-most periods than in the oldest ones. The observed reduction in both the duration and cumulative rainfall of the triggering rainfall events may reflect a change in the rainfall patterns in the region, with a shift toward shorter, more impulsive precipitation patterns. However, the use of daily rainfall measurements, necessitated by the length of the data series, likely underestimates the real intensity of these events. Moreover, the changes in the triggering conditions (Table 1, Fig. 3a, b) may also be connected to the shift in the seasonality of RELs (Fig. 2b), with the decrease in the number of RELs in autumn (SON), which is a season characterized by severe events in region, as well as in the whole Mediterranean area. The temporal analysis and the threshold calculation were here carried out using an empirical approach, which has its pros and cons. The primary advantage is the possibility to apply the same method to different study areas where similar data are available, enabling a quantitative comparison of the results. Furthermore, an empirical approach can be effectively combined with climate modelling to evaluate past changes and project future variations (Gariano and Rianna, 2025). On the other hand, a disadvantage of any empirical approach is the requirement for a sufficiently long and complete series of data, which is particularly important when evaluating spatial and temporal variations in landslides activity due to global changes. Incomplete or short series of records limit the ability to properly evaluate the changes and the possible impact of climate and environmental changes on landslide frequency and distribution. The catalogues used in this work can be considered accurate and complete with regard to rainfall-induced landslides that have caused damage to people, property, and infrastructure, and therefore have been reported by relevant information sources. The general increase in the number of RELs during the years should not be linked to the overall human occupation of the region; indeed, an examination of the population data available from Censuses conducted by the Italian National Institute of Statistics shows that, between 1921 and 1951 the number of residents has raised from around 1.7 to 2 million and then has remained steady over the decades, with a slight downward trend beginning at the start of the 21st century. The high number of RELs recorded in the main provincial capitals highlights on the one hand more comprehensive information in areas with more citizens (residents and workers), also linked to demographic trends in the analysed period, with a large proportion of the population that has moved to the main towns and, consequently, an increase in the number of people witnessing the landslides. On the other hand, a higher number of landslides in urban areas highlights the potential negative role of urban expansion and land-use changes in slope stability. An underestimation in the number of landslides in the older period of the series (1921–1950) was unavoidable, due to the reduced availability of the sources of information. In contrast, the increase in the number of records starting from the 2000s (cf. Fig. 2a) can be attributed to the increasing availability of online sources, which has vastly improved the reporting of even minor events, compared to previous decades, in which

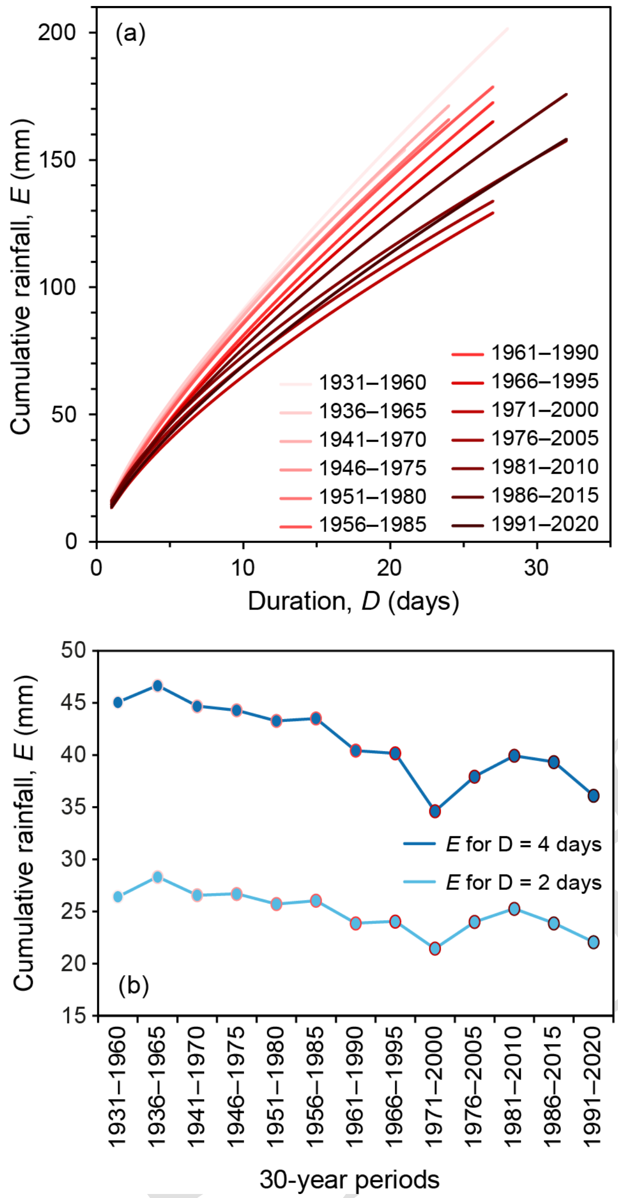

Figure 3. (a) Rainfall thresholds defined for the 30-year moving windows from 1931 to 2020 in the study area. Threshold equations and details are listed in Table 1. The regions of uncertainty of the thresholds are not shown. **(b)** Cumulative rainfall threshold values for durations of 2 and 4 d, for the 30-year moving windows from 1931 to 2020 in the study area.

the information came mostly from hardcopies and archives. Notably, this increase in documentation occurred despite a slight decrease in the regional population over the same period.

It should be remarked that rainfall thresholds defined using rainfall data with coarse temporal resolution, which is almost unavoidable when long historical series of landslide and rainfall data are analysed as in this work, have been proven to being characterized by high uncertainty and underestimation, which hinders their application for operational landslide prediction purposes (Gariano et al., 2020). The underestimation becomes evident when the thresholds here defined are compared with the one defined by Vennari et al. (2014) for the same region, using landslide information for the period 1996–2011 and hourly rainfall data, whose equation is $E = (8.6 \pm 1.1) \cdot D^{(0.41 \pm 0.03)}$, in which D, contrarily to this work, is expressed in hours. The cumulative rainfall values for duration of 1, 2, and 4 d (24, 48, and 96 h) calculated using the thresholds here defined for the 30-year period 1986–2010 (14.3, 23.9, and 39.3 mm, respectively, cf. Table 1) are significantly lower than the same values calculated using the threshold defined by Vennari et al. (2014) (31.7, 42.1, and 55.9 mm, respectively), with percentage reduction ranging from 37 % to 57 %. However, the thresholds here defined were calculated solely for the purpose of analysing long-term changes in the triggering conditions of the RELs occurred in Calabria between 1921 and 2020. They should be utilized for long-term territorial planning and hazard assessment, while their use in landslide early warning systems is not advisable for the above-mentioned reasons.

5 Conclusions

This study provides an update on the long-term analysis of the changes in the temporal distribution of rainfall-induced landslides recorded in Calabria, southern Italy, over a century (1921–2020), and of their triggering rainfall conditions defined and evaluated using a consolidated approach. The main findings can be summarized as follows:

- A significant rise in the occurrence of Rainfall Events with Landslides (RELs) has been observed since 2009 (Fig. 2a). While this is partially influenced by the increased availability of information sources (mostly online), it also reflects a period of heightened hydro-meteorological activity in the region. No significant variations in the number and distribution of rain gauges over the recent 10 years (2011–2020) compared to the previous decade (2001–2010) can be observed (Fig. 1b).

- The temporal distribution of the RELs changed, with a noticeable increase in events during spring (MAM) and a decrease in autumn (SON), suggesting a variation in the regional landslide-triggering seasonality (Fig. 2b).

- The rainfall conditions triggering landslides show an overall decreasing trend. In the recent 30-year periods landslides are triggered by rainfall events of shorter duration and lower cumulative amounts if compared to the cases of early 20th century (Fig. 3a). This is detectable by evaluating average values of duration and cumulative rainfall (Table 1), as well as by analysing the threshold values for typical durations (2 and 4 d), which also show a decreasing trend (Fig. 3b). The lowering of the landslide-triggering rainfall may be also linked to the increase in the number of RELs in spring and the decrease in autumn, being the latter characterized by more severe rainfall in the region.

These general findings on the one hand suggest a change in rainfall patterns triggering landslides in the region and on the other hand may indicate an increased propensity of the territory to generate landslides, even with less severe triggering rainfall events, likely driven by a combination of climate change and anthropogenic factors.

In conclusion, the use of rainfall thresholds calculated over moving windows proves to be a robust approach for evaluating the evolution of triggering conditions over time. The dynamic analysis allowed the detection of trends that were previously less detectable through static sub-period comparisons. Such approach proved satisfactory in evaluating long-term changes in the number, seasonality and triggering conditions of rainfall-induced landslides. However, rainfall thresholds derived from low-resolution rainfall data (i.e., daily measurements) can be used for long-term comparative analysis but suffer from uncertainty and underestimation, which hinders their practical application in operational landslide prediction. The methodological procedure can be easily replicated in other areas where a similar dataset is available, making it useful for comparisons. In this regard, the authors advocate the essential role of data collection and archiving of accurate and comprehensive records of landslide activations and occurrences, acquired according to common standards and procedures, for any kind of landslide analysis and modelling purposes.

Data availability. Data used in this work can be provided by the authors upon reasonable requests.

Author contributions. S.L.G. and OP: conceptualisation and writing original draft, review, and editing. S.L.G.: rainfall data collection and analysis. O.P.: landslide activation data collection and analysis.

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