https://doi.org/10.18485/resylab.2024.6.ch3

Prediction of rainfall-induced landslides in a changing climate: issues and perspectives for regional-scale approaches

Stefano Luigi Gariano

CNR-IRPI (Italian National Research Council – Research Institute for Geo-Hydrological Protection), via Madonna Alta 126, Perugia, Italy, stefanoluigi.gariano@cnr.it

Abstract Global warming is unequivocal. An increase in the frequency and magnitude of intense rainfall events was observed in several areas of the World and more changes are expected. This has major implications for operational landslide prediction, given that the effects of climate change on landslides are difficult to determine and to predict. As a matter of fact, regional-scale landslide early warning systems, usually based on rainfall-related prediction tools and susceptibility zonation, need to consider these effects and the related variations. In Italy, where landslides are mainly triggered by intense and/or prolonged rainfall, several investigations were carried out for the prediction of rainfall-induced landslides, for the implementation of landslide early warning systems and for the evaluation of the role of climate and environmental changes (mostly rainfall and land use) on landslide activity, occurrence, and frequency. In this contribution, a brief overview of the defined methods, models and tools is presented. Special emphasis is placed on the definition of rainfall thresholds defining the minimum triggering conditions for the initiation of shallow landslides, given their usability in regional and national warning systems and in the evaluation of changes in the triggering conditions of the landslides. Issues and perspectives of regional-scale analyses of the ongoing and expected effects of climate change on rainfall-induced landslides are discussed.

Keywords landslides, rainfall, climate change, climate projections, landslide prediction, rainfall thresholds, Italy

Introduction

According to the last report of the International Panel on Climate Change (IPCC 2023), human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts and related losses and damages to nature and people.

The last annual report of the International Disaster Database (CRED 2023) recorded 387 natural disasters worldwide in 2022 that affected 185 million individuals and caused 30,704 deaths, with economic losses that totalled around 223.8 billion US$. A partial estimate for 2023 counted a 30% increase in the number of deaths (compared to 2022) due to climate-related events (i.e., floods, wildfires, cyclones, storms, and landslides) and a 60% rise in the number of deaths from landslides, globally.

The Global Fatal Landslide Database lists 4862 non-seismic landslides that caused 55 997 deaths worldwide in the period 2004-2016 (Froude and Petley 2018). In a European survey, 849,543 landslides were mapped in 20 national inventories (Herrera et al. 2018). Within Europe, Italy experiences a large number of landslides and related damage, with more than 622,000 landslides mapped by the Italian Institute for Environmental Protection and Research, covering about 8% of the national territory (https://idrogeo.isprambiente.it/app/). According to the last Polaris report by the Research Institute for Geo-Hydrological Protection of the Italian National Research Council (CNR-IRPI), between 1973 and 2022, landslides caused 144,806 people homeless or evacuees, 1077 deaths, 10 missing and 1443 injured persons in all the 20 administrative Italian regions (Bianchi and Salvati 2023; https://polaris.irpi.cnr.it/). Some severe rainfall events hit the Italian territory in 2022 and 2023, triggering thousands of landslides and causing dozens of victims (e.g., Donnini et al. 2023; Romeo et al. 2023; Ferrario and Livio 2024).

Individual landslides do not affect wide areas as floods, megafloods, and earthquakes; however, they are numerous and they occur frequently in hilly and mountainous areas. Landslides are complex and very diversified phenomena whose ranges of measures encompass different orders of magnitude (Guzzetti et al. 2012). Given the high spatial and temporal variability of the landslides, climate (and its change) can affect them in multiple ways and at different temporal and geographical scales (Gariano and Guzzetti 2016). The landslide response to climate change varies depending on the landslide type and size, and on the local stability or instability conditions. The response is different for first-time shallow failures and for the reactivation of large deep-seated landslides. Overall, the increase in frequency and intensity of the rainfall events may results in a change in the frequency, abundance, and location of rapid and very rapid landslides, mostly shallow slides and debris flows, which are the primary cause of landslide casualties, and therefore deserve particular attention. Nevertheless, these issues are often neglected in the operational prediction of rainfall-induced landslides (Gariano and Guzzetti 2022).

According to many literature reviews, Italy had a pivotal role in the preparation of a relevant number of studies in the topics of rainfall-induced landslide prediction (mostly with rainfall thresholds, Guzzetti et al. 2008; Chae et al. 2017; Segoni et al. 2018; Gariano et al. 2020a; Gonzalez et al. 2024), susceptibility assessment

(Reichenbach et al. 2018), and early warning (Piciullo et al. 2018; Guzzetti et al. 2020), as well as in the evaluation of the role of climate and environmental changes (mostly rainfall and land use) on landslides (Crozier 2010; Gariano and Guzzetti, 2016, 2022; Jakob 2021).

In this paper, a brief overview of methods and models for the prediction of the occurrence and activity of rainfall-induced landslides in a changing climate is presented, with an eye for regional-scale, empirical analyses.

Background

Main approaches to evaluate the relationships between rainfall and landslides

The relationships between rainfall and landslide occurrence/activation are generally modelled using two approaches (Guzzetti et al. 2022): physically-based (or deterministic) and empirical (or statistical). The first approach relies on numerical models and necessitates an extensive collection of precise hydrogeological and geotechnical variables to compute a factor of safety, which indicates the ratio between the local resisting and driving forces. The latter approach involves the statistical analysis of past rainfall conditions linked to landslide initiation, obtained by combining rainfall series with the dates at which slope movements occurred or were activated. To distinguish between conditions that likely trigger or do not trigger landslides, empirical relations have to be established using threshold values or functions. In most cases, the analysis results in the calculation of rainfall thresholds for landslide initiation.

Main approaches to evaluate the role of climate change on landslides

Three main approaches are employed to assess the role of climate change on the occurrence, frequency, and activity of landslides (Gariano and Guzzetti 2016, 2022): (i) the implementation of numerical climate and landslide models, i.e. the use of rainfall projections, generated by downscaled and bias-corrected global climate models, as input to slope stability and landslide hazard models of different types (modelling approach); (ii) the execution of empirical analyses of landslides and climatic (mostly rainfall and temperature) records, usually over a period that last from 30 to around 100 years, attempting at assessing geographical and temporal variations in landslides activity (empirical approach); (iii) the study of paleo-evidences of landslides, proxy climate indicators, and climate data, in a time range that covers the period from 40,000 BP to the 20th century. In recent years, there has been a significant rise in the amount of studies that have used a modelling approach to examine the relationships between landslides and climate at the basin, regional, and national scales (Gariano and Guzzetti 2022; Gariano and Rianna 2024). In some cases, the empirical and the modelling approaches were successfully coupled.

Landslide prediction in a changing climate

Empirical rainfall thresholds: definition and usability

Empirical rainfall thresholds have become the most used tools to analyse the triggering conditions of slope failures and to predict the possible occurrence of a landslide or of a population of landslides in a given area (Segoni et al. 2018; Guzzetti et al. 2020; Gonzalez et al. 2024).

Among the diverse methods adopted to calculate thresholds, the frequentist method (Brunetti et al. 2010; Peruccacci et al. 2012) has become the most used worlwide. This method is based on a frequency analysis of the empirical rainfall conditions that have resulted in known landslides in a given period and in a given area. The threshold is modeled by a power law relationship between cumulated event rainfall E (in mm) and the rainfall duration D (generally in hours, also in days), according to equation [1]:

$$E = (\alpha \pm \Delta\alpha) D^{(\gamma + \Delta\gamma)} \qquad [1]$$

where α is the intercept (the scaling parameter) and γ is the slope (the scaling exponent) of the curve, and Δα and Δγ are the uncertainties associated with α and γ, respectively. The method allows the calculation of objective and reproducible thresholds at different non-exceedance probabilities, and the uncertainties associated with the threshold parameters. The 5% non-exceedance probability threhsolds is usually calculated, as a reference with previous works.

To define reliable thresholds, a large amount of accurate spatial and temporal information on landslides induced by rainfall in a given study area (generally collected in a catalogue, e.g. Peruccacci et al. 2023) is needed. A tool for the objective and reproducible identification of the rainfall conditions likely responsible for landslide triggering and the calculation of frequentist rainfall was implemented using the R open-source software and is freely downloadable (Melillo et al. 2018). Details on the methods and tools needed to define rainfall threhsolds with the frequentist method can be found in Guzzetti et al. (2022) and references therein.

Using a catalogue of 2309 rainfall events responsible for the occurrence of shallow landslides in Italy between 1996 and 2014, national and regional thresholds for climate and meteorological domains in the Italian territory were defined by Peruccacci et al. (2017). In particular, five classes distinguished by a progressive average annual precipitation were considered and the frequentist rainfall thresholds for the landslides that occurred in each area were calculated. A key observation was that regions with higher mean annual precipitation values were characterized by higher and steeper thresholds. In more rainy areas, the landscape requires a greater amount of rainfall to trigger landslides, compared to less rainy areas with comparable environmental conditions. This finding suggests that the landscape adapts to the rainfall patterns prevalent in the area. A relevant implication is that when and where the weather regimes undergo a transformation as a consequence of global warming, the thresholds are anticipated to change, and the operational prediction systems (mostly based on thresholds) will also necessitate corresponding adjustments.

Frequentist rainfall threholds can be also used to assess the variations in the landslide-triggering conditions over long periods, both in the past and in the future (using landslide-climate simulations), as described below.

Changes in landslide-triggering conditions: a look at the past

Adopting an empirical approach at the regional scale, the variations in the occurrence of rainfall-induced landslides in Calabria region, southern Italy, in the 90-year period 1921-2010 were analysed (Gariano et al. 2015). In particular, using a catalogue of 7000 landslides and daily rainfall data recorded by 318 rain gauges, 1466 rainfall events with landslides (RELs) were reconstructed in the investigated period. A rainfall event with landslides was defined as the occurrence of one or more landslide during or shortly after a rainfall event. Fig. 1 shows the flowchart and data used in to reconstruct the RELs and their temporal and spatial distribution.

The dataset was split in three 30-year sub-periods (1921-1950, 1951-1980, and 1981-2010) and the changes in the spatial and temporal distribution of the RELs, as well as the changes in the landslide-triggering rainfall conditions and in the impact of the landslides to the population were evaluated. For the spatial analyses, the municipality boundaries were used as units of analysis; for the assessment of the landslide impact to the population, the number of RELs in each municipality was ratioed to the number of inhabitants per municipality measured by national censuses conducted in 1951, 1981, and 2011.

Changes in the geographical and the temporal distributions of the RELs were observed, with a particular concentration of the events in the late winter and early spring in the recent-most 30-year period. A rise of approximately 40% in the population living in municipalities with increased impact posed by the landslides was observed; this was ascribed to a confluence of climate-related and societal transformations in the region over the investigated period.

The landslide-triggering rainfall conditions were evaluated calculating the duration (*D*) and the cumulated rainfall (*E*) of the RELs that occurred in each of the three defined 30-year periods. Lower values of the average and maximum cumulated event rainfall that have resulted in landslides were observed in the recent-most 30-year period 1981–2010 than in the previous periods. This can be considered a proxy of an increased vulnerability of the territory, which need less rainfall to trigger a landslide than in the past.

An update of that work is here proposed, with the calculation of the frequentist, landslide-triggering rainfall thresholds for several 30-year periods defined using a moving window with a 5-year step, rather than only for the three separated 30-year periods. This results in thirteen periods and, consequently, thirteen thresholds, allowing a more precise evaluation of the changes. Tab. 1 lists the mean values of *D* and *E* for the rainfall events that have induced landslides in the thirteen 30-year periods and the equations of the related thresholds. Fig. 2 shows the thirteen thresholds and Fig. 3 shows the how the threshold parameters change over time.

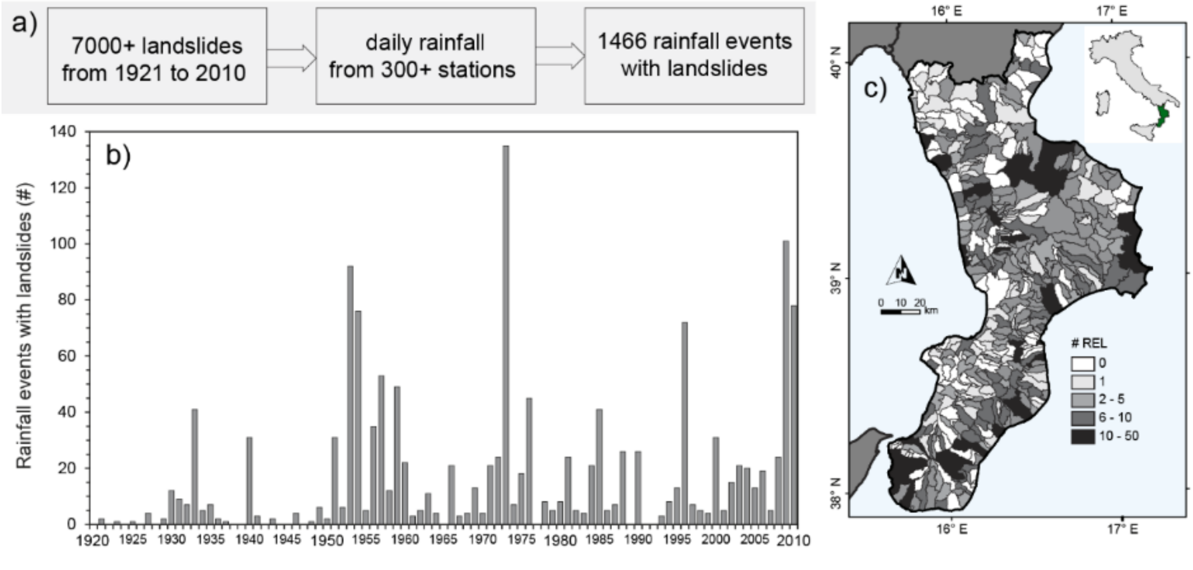

Figure 1 a) Flowchart and data used for the reconstruction of the rainfall events with landslides (RELs). b) Temporal distribution of the 1466 RELs occurred in Calabria region, Italy, from 1921 to 2010. c) Geographical distribution of the RELs in the municipalities of the Calabria region. Modified from Gariano et al. (2015).

Table 1 Parameters of the *ED* frequentist thresholds at 5% non-exceedance probability calculated for different 30-year periods in Calabria region, southern Italy. Key: Threshold equations according to eq. [1]; *D*, rainfall duration (in days); *E*, cumulated event rainfall (in mm).

Period	Threshold equation	Mean D(day)	Mean E(mm)
1921-1950	$E = (11.1 \pm 1.4)D^{(0.93+0.05)}$	7.3	232.1
1926-1951	$E = (12.1 \pm 1.1)D^{(0.87+0.04)}$	6.8	282.5
1931-1960	$E = (15.5 \pm 1.3)D^{(0.77+0.04)}$	7.9	253.2
1936-1965	$E = (17.2 \pm 1.5)D^{(0.72+0.04)}$	7.8	242.9
1941-1970	$E = (15.8 \pm 1.4)D^{(0.75+0.04)}$	7.9	240.5
1946-1975	$E = (16.1 \pm 1.4)D^{(0.73+0.04)}$	7.5	236.3
1951-1980	$E = (15.3 \pm 1.2)D^{(0.75+0.04)}$	7.2	225.7
1956-1985	$E = (15.6 \pm 1.4)D^{(0.74+0.04)}$	7.0	196.0
1961-1990	$E = (14.1 \pm 1.4)D^{(0.76+0.05)}$	6.4	182.7
1966-1995	$E = (14.4 \pm 1.5)D^{(0.74+0.05)}$	6.2	180.9
1971-2000	$E = (15.5 \pm 1.5)D^{(0.69+0.05)}$	5.7	176.4
1976-2005	$E = (15.2 \pm 1.4)D^{(0.66+0.05)}$	5.4	145.7
1981-2010	$E = (16.0 \pm 1.2)D^{(0.66+0.04)}$	6.6	167.2

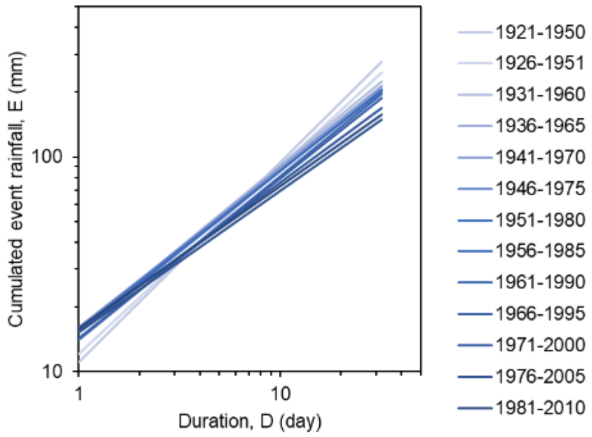

Figure 2 *ED* rainfall thresholds defined for thirteen 30-year moving windows from 1921 to 2010 in Calabria region, southern Italy. The regions of uncertainty of the thresholds are not shown.

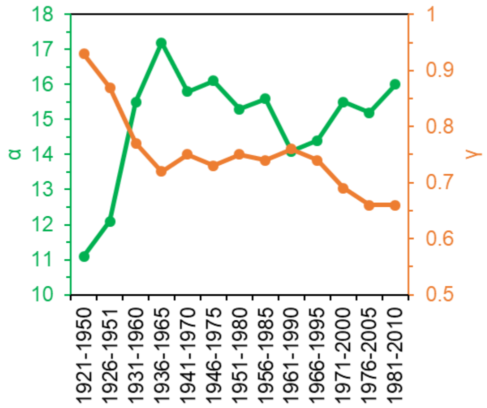

Figure 3 Values of the parameters of the frequentist thresholds defined for thirteen 30-year moving windows from 1921 to 2010 in Calabria region, southern Italy.

A slight decrease in the mean values of the duration of the landslide-triggering rainfall events and a marked decrease in the mean values of the cumulated rainfall can be observed, indicating a trend in the increase of the propensity of the landscape to generate landslides, even with less rain needed. Moreover, an increase in the α parameter and a decrease in the γ parameter during time is clearly visible. The thresholds become higher and less steep in the recent years, meaning that, in the study area, the landslide-triggering rainfall events of short durations were characterized by higher cumulated rainfall, i.e. they became more intense.

The same approach described in Gariano et al. (2015) was applied in Umbria, a region in Central Italy (Gariano et al. 2021), to investigate changes in the spatial distribution and temporal occurrence of 453 rainfall-induced landslides that occurred from 1928 to 2001. Landslide-triggering rainfall thresholds can be defined also in this case by adopting the frequentist approach. However, due to a lower number of RELs in the first part of the observation period, reliable thresholds can be defined only for the period 1971-200. Tab. 2 lists the mean values of *D* and *E* for the rainfall events that have induced landslides in five 30-year periods and the equations of the five related thresholds. Landslide-triggering rainfall events underwent changes in characteristics over the observation period also in this area. Specifically, the landslides occurred in the recent most period were triggered by rainfall events with on average lower cumulated rainfall and shorter duration, especially during the winter and early spring seasons. The propensity of this area to generate landslides has also increased with time. Moving forward through time, the landslide-triggering rainfall thresholds became flatter also in this area.

Table 2 Parameters of the *ED* thresholds at 5% non-exceedance probability calculated for five 30-year periods in Umbria region, central Italy. Key: Threshold equations according to eq. [1]; *D*, rainfall duration (in days); *E*, cumulated event rainfall (in mm).

Period	Threshold equation	Mean D(day)	Mean E(mm)
1951-1980	$E = (14.8 \pm 1.7)D^{(0.47+0.06)}$	4.3	80.3
1956-1985	$E = (14.5 \pm 1.3)D^{(0.48+0.06)}$	4.2	76.1
1961-1990	$E = (14.4 \pm 1.0)D^{(0.46+0.05)}$	4.2	72.5
1966-1995	$E = (15.6 \pm 1.0)D^{(0.44+0.05)}$	3.7	72.6
1971-2000	$E = (16.8 \pm 1.0)D^{(0.41+0.04)}$	3.6	77.6

The results obtained in both cases may seem contrasting at first glance. However, such findings indicate that, in the studied areas, on the one hand the mean values of the cumulated rainfall associated with landslides were lowering, suggesting that less rainfall was needed to trigger landslides in the recent-most years than in the past. On the other hand, the distribution (in the *D-E* space) and the characteristics of landslide-triggering conditions, which shapes the threshold curves, was changing over time. In particular, the short-term landslide-triggering rainfall conditions became characterized by higher cumulated rainfall in the recent-most years, while the ones with long durations had lower cumulated rainfall. These findings can be relevant for scientific purposes and practical applications, e.g. land planning and design of operational systems for landslides prediction.

Other examples in which rainfall thresholds, either empirical or physically-based, were used to evaluate past and future changes in landslide triggering conditions in Italy can be found in Rianna et al. (2017, 2020), Alvioli et al. (2018), Sangelantoni et al. (2018).

Changes in landslide-occurrence: a look towards the future

A well-populated historical catalogue of rainfall events with landslide like the one collected in Calabria region is also useful to define a calibration set for climatic models, in order to evaluate possible future landslide projections. Indeed, using the recent part of the catalogue of RELs occurred in Calabria (specifically the last 30-year period 1981–2010, which lists information about 600 landslides) and daily rainfall measurements in the same period, empirical correlations between landslide occurrence and two climate variables assumed to be proxies for landslide activity, i.e. mean annual rainfall and seasonal cumulative rainfall, were defined (Gariano et al. 2017). A good correlation was found between the mean annual rainfall and the number of rainfall events with landslides.

Combining this correlation laws with mid-term (2036–2065) projections of the mean annual rainfall obtained for two climate scenarios (i.e., Representative Concentration Pathways RCP4.5 and RCP8.5), future scenarios for possible landslide occurrence in the region were defined. In particular, the CMCC_CM (Scoccimarro et al. 2016), with a horizontal resolution of about 80 km, was used as Global Circulation Model in the simulation chain. Moreover, a dynamical downscaling through the COSMO_CLM model (Bucchignani et al. 2015) at 8 km resolution was adopted.

Results outlined an increase in landslide occurrence in the future period 2036–2065, in both scenarios: +21.2% for the “mid-way” RCP4.5 scenario and +45.7 for the more pessimistic RCP8.5 scenario. This experiment showed that the empirical and the modelling approaches can be successfully combined. Furthermore, using projections of population data for the year 2065, the variations in the impact of RELs on the population of the region of Calabria in the future period 2036–2065 were assessed using the same methods proposed in Gariano et al. (2015). A relevant increase in the landslide impact to the population was modelled for both climate scenarios. Such changes can be due to either changes in the number of the rainfall-induced landslides and in the number of the exposed elements (only population in this case).

Since a catalogue of landslides that caused damage to citizens, properties, and infrastructures was used for these works, the obtained results can be useful for societal and land planning, and the definition of actions for landslide risk management in the study area.

The role of land use/cover in landslide occurrence

The evaluation of the role of land use/cover on landslides is a remarkable topic (e.g. Sidle and Ochiai 2006). The effects of climate change on vegetation, soil, land use and land cover, together with the associated feedback processes, contribute to more intricate interactions within an already challenging assessment.

An assessment of spatial and temporal variations in landslide occurrence at regional scale under the effect of land use/cover changes was also conducted in Calabria region (Gariano et al. 2018). The complete record of landslides that were recorded in the region from 1921 to 2010, together with land use/cover maps from 1956 (from the Italian National Research Council and the Italian Touring Club) and 2000 (from CORINE land cover project), and future estimates of projected land use/cover changes at 2050 (an ensemble of 32 simulations from the LUC@CMCC model; Santini and Valentini, 2011) were employed. Empirical relationships linking the observed land use/cover variations to landslide occurrence were defined. The modelling findings indicated that landslide occurrence increased across the majority of the regional territory. However, it was observed that land use changes that imply agricultural practices and land management that can mitigate landslide occurrence had positive local effects. Regarding the future, the landslide projections conditioned to the land use/cover change ensemble reveal an overall, modest increase in landslide occurrence in all scenarios. An increase in the number of landslides due to land use/cover variations was projected in 291 municipalities in Calabria (71%), with 4 municipalities where the increase is expected to exceed 50%. In this case, too, the results may suggest a join in the climate and social factors involved.

Other examples in which land use/cover and their changes were considered to evaluate past and future changes in landslide occurrence in Italy can be found in Reichenbach et al. (2014), Lonigro et al. (2017), Persichillo et al. (2017), and Pisano et al. (2017).

Discussion and perspectives

The majority of the research works that attempted to assess how the observed and expected climatic and environmental changes might affect landslides looked at case studies in Europe. Most basin-, regional-, and national-scale studies model the links between landslides and climate using empirical and statistical analyses (Gariano and Guzzetti 2022; Gariano and Rianna 2024).

In this contribution, a brief overview on the possible use of empirical analyses and models for the quantitative evaluation of the impact of climate change on landslide at the regional scale is presented, with a focus on applications in Italy, which is the country with the largest number of applications and case studies on this topic.

The use of an empirical approach has pros and cons. The primary advantage is the possibility to apply the same method to different study areas where similar data is available, so allowing a quantitative comparison of the results. Moreover, an empirical approach can be effectively combined with a climate modelling chain, to evaluate not only the changes in the past but also the expected future variations.

A relevant issue in the adoption of the climate modelling chain (Rianna et al. 2014; Gariano and Guzzetti 2016) is the selection of the global circulation models, of the technique to downscale to a regional model, of the bias correction methods and of the concentration scenario. The selection of only “extreme” scenarios is not advisable, while the adoption of ensembles guarantee more reliable results (Jakob 2021). Furthermore, considering that an increasing number of countries are now requiring the reduction of carbon emissions by a given time horizon, if the current policies remain as ambitious until 2100, the “business-as-usual” scenario (RCP 8.5) is not the most probable outcome, but rather an extreme possibility. For this reason, it should not always be used as the worst-case scenario in modelling applications; conversely the use of more realistic scenarios could lead to more effective policy-making (Hausfather and Peters 2020).

A downside of any empirical approach is the need of a sufficiently long series of data, which is even more important in the evaluation of spatial and temporal variations in landslide activity due to global changes. An incomplete or poorly extended series of climate and landslide records limits the possibility to properly evaluate the impact of the climate and environmental changes on landslide frequency and distribution (Crozier 2010). Regardless of the approach used to model the relationships among rainfall and landslides (and their changes), accurate and complete records of landslides and their consequences, preferably collected with common standards and procedures, are needed for modelling purposes. The catalogues used in the works discussed here (Gariano et al. 2015, 2017, 2018, 2021) can be considered accurate and complete with regard to rainfall-induced landslides that have caused damage to people, property, and infrastructure in the study areas, and have been reported by relevant information sources. Moreover, a sufficiently long series of climate records (at least 30 years,) is necessary to effectively eliminate interannual fluctuations and anomalies, while still capturing longer-term climate patterns.

A key question in the application of a model at the regional scale is the choice of the unit of analysis. In the works described in this contribution, the municipality boundaries were selected as reference spatial unit, to evaluate spatial changes, assess landslide impact, assign a land use/cover class. This choice enabled an effective matching between environmental and socio-economic data. However, the methods discussed in this contribution can be applied adopting different units of analysis.

A noteworthy issue is that the rainfall thresholds defined using long series of past landslide and rainfall data to evaluate their spatial and temporal variations, as in the cases here presented, should not be applied to operational landslide prediction. Utilizing data series that span extensive periods of time (especially in the past) imply the use of rainfall data with coarse temporal resolution (e.g. daily rainfall series), which is proved to be a cause of high uncertainty and underestimation of landslide-triggering rainfall thresholds (Gariano et al. 2020b), hampering their application in operational landslide early warning systems.

The evaluation of uncertainties in landslide prediction or in the evaluation of the role of climate change on landslide activity is frequently overlooked. Despite the relevant improvements achieved in the recent years in all components of the landslide-climate modelling chain, significant epistemic and aleatory uncertainties are expected to persist. Their evaluation (and communication) is crucial. The quantification and the reduction of the uncertainties in landslide projections can be achieved improving the methods for landslide modelling, and using ensembles of climate projections, which is more common now than in the past.

An important challenge in assessing the impact of climate change on landslides is the limited overlap between the temporal (short and long term) and geographical (local, regional, global) scales of climate analysis and landslide phenomena (Gariano and Guzzetti 2016; 2022). This discrepancy makes modelling and extrapolation increasingly complex. It should be remarked that simple inferences linking climate change to an increase in landslide activity can be erroneous (Jakob 2021). The complexity of the situation prevents the definition of a single approach suggesting the way of a multidisciplinary, holistic approach (Picarelli et al. 2016). Quantitative, regional-scale analyses in which historical and modelling approaches are combined to evaluate the impact of observed and projected rainfall variations on the frequency or magnitude (or both) of landslides of various types and in different physiographical settings could led to reliable results and reduce all the inherent uncertainties.

In addition, in the evaluation of strategies for the mitigation of landslides risk in a changing world, it should be taken in mind that climate and its variations have a significant influence on both environmental and socio-economic elements, with several feedback mechanisms (Pasini et al. 2018). Climate change has an influence on both landslide activity and landscape vulnerability (e.g. due to changes in land use); the exposure of population and infrastructure to landslides is closely linked to the socio-economic conditions of the affected regions. In some cases, variations in environmental or socio-economic factors could have impacts on landslides even higher than climate change. Such issues are also crucial in the definition of effective adaptation measures.

Conclusions

The evaluation of the effects of climate and environmental changes on landslides is, and will remain, a relevant and noteworthy research topic, which requires appropriate funding and political support. With good efforts, the prediction of rainfall-induced landslides in a changing environment is feasible and can help reduce landslide hazard and risk. Rigorous approaches, either empirical or physically-based, should be based on accurate and complete (as much as possible) landslide records and climate series, with the aim of reducing the uncertainties in the modeling results. Regional-scale analyses, looking at both the (observed) past and the (projected) future, provide comprehensive insight into the relationship between climate change and landslides, which can have useful implications for decision-making and the design of adaptation strategies.

A comprehensive and interdisciplinary strategy is needed to understand and quantify the impact of climatic factors and their changes on landslides, especially in the assessment of landslide hazard and risk.

Acknowledgements

The work described here is the outcome of the studies I began during my PhD and continued during my research activities, thanks to the collaboration of many colleagues. I would like to thank in particular Maria Teresa Brunetti, Fausto Guzzetti, Massimo Melillo, Silvia Peruccacci, Olga Petrucci, and Guido Rianna, whose contributions were crucial for the realization of this work.

References

Alvioli M, Melillo M, Guzzetti F, Rossi M, Palazzi E, von Hardenberg J, Brunetti MT, Peruccacci S (2018) Implications of climate change on landslide hazard in Central Italy. Science of the Total Environment. 630:1528–1543. https://doi.org/10.1016/j.scitotenv.2018.02.315

Bianchi C, Salvati P (2023) Rapporto Periodico sul Rischio posto alla Popolazione italiana da Frane e Inondazioni. Anno 2023, Istituto di Ricerca per la Protezione Idrogeologica (IRPI), Consiglio Nazionale delle Ricerche (CNR) https://doi.org/10.30437/report2023 (in Italian)

Bucchignani E, Montesarchio M, Zollo AL, Mercogliano P (2015) High-resolution climate simulations with COSMO-CLM over Italy: performance evaluation and climate projections for the 21st century. International Journal of Climatology 36(2):735–756. http://dx.doi.org/10.1002/joc.4379

Brunetti MT, Peruccacci S, Rossi M, Luciani S, Valigi D, Guzzetti F (2010) Rainfall thresholds for the possible occurrence of landslides in Italy. Natural Hazards and Earth System Sciences 10:447–458. https://doi.org/10.5194/nhess-10-447-2010

Donnini M, Santangelo M, Gariano SL, Bucci F, Peruccacci S, Alvioli M, Althuwaynee O, Ardizzone F, Bianchi C, Bornaetxea T, Brunetti MT, Cardinali M, Esposito G, Grita S, Marchesini I, Melillo M, Salvati P, Yazdani M, Fiorucci F (2023) Landslides triggered by an extraordinary rainfall event in Central Italy on September 15, 2022. Landslides 20:2199–2211. https://doi.org/10.1007/s10346-023-02109-4

Chae B-G, Park H-J, Catani F, Simoni A, Berti M (2017) Landslide prediction, monitoring and early warning: a concise review of state-of-the-art. Geosciences Journal 21:1033–1070. https://doi.org/10.1007/s12303-017-0034-4

CRED (2023) 2022 Disasters in numbers Centre for Research on the Epidemiology of Disasters, Brussels. https://cred.be/sites/default/files/2022_EMDAT_report.pdf

Crozier MJ (2010) Deciphering the effect of climate change on landslide activity: a review. Geomorphology 124.260–267. http://dx.doi.org/10.1016/j.geomorph.2010.04.009

Ferrario MF, Livio F (2024) Rapid Mapping of Landslides Induced by Heavy Rainfall in the Emilia-Romagna (Italy) Region in May 2023. Remote Sensing 16(1):122. https://doi.org/10.3390/rs16010122

Froude MJ, Petley DN (2018) Global fatal landslide occurrence from 2004 to 2016. Natural Hazards and Earth System Sciences 18:2161–2181. https://doi.org/10.5194/nhess-18-2161-2018

Gariano SL, Guzzetti F (2016) Landslides in a changing climate. Earth-Science Reviews. 162:227-252. https://doi.org/10.1016/j.earscirev.2016.08.011

Gariano SL, Guzzetti F (2022) Mass-Movements and Climate Change. Treatise on Geomorphology (Second Edition). 5:546-558. https://doi.org/10.1016/B978-0-12-818234-5.00043-2

Gariano SL, Petrucci O, Guzzetti F (2015) Changes in the occurrence of rainfall-induced landslides in Calabria, southern Italy, in the 20th century. Natural Hazards and Earth System Sciences. 15:2313–2330. https://doi.org/10.5194/nhess-15-2313-2015

Gariano SL, Rianna G, Petrucci O, Guzzetti F (2017) Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale. Science of the Total Environment. 596-597:417-426. https://doi.org/10.1016/j.scitotenv.2017.03.103

Gariano SL, Petrucci O, Rianna G, Santini M, Guzzetti F (2018) Impacts of past and future land changes on landslides in southern Italy. Regional Environmental Change. 18:437-449. https://doi.org/10.1007/s10113-017-1210-9

Gariano SL, Segoni S, Piciullo L (2020a) Advances in rainfall thresholds for landslide triggering in Italy. In: Applied Geology. Springer, pp. 247–263. https://doi.org/10.1007/978-3-030-43953-8_15

Gariano SL, Melillo M, Peruccacci S, Brunetti MT (2020b) How much does the rainfall temporal resolution affect rainfall thresholds for landslide triggering? Natural Hazards 100:655–670. https://doi.org/10.1007/s11069-019-03830-x

Gariano SL, Verini Supplizi G., Ardizzone F., Salvati P., Bianchi C., Morbidelli R., Saltalippi C (2021) Long-term analysis of rainfall-induced landslides in Umbria, central Italy. Natural Hazards 106(3):2207-2225. https://doi.org/10.1007/s11069-021-04539-6

Gariano SL, Rianna G (2024) Modelling approaches to evaluate the role of climate change in landslide activity in Europe, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-14725, https://doi.org/10.5194/egusphere-egu24-14725

Gonzalez FCG, Cavacanti MDCR, Nahas Ribeiro W, Mendonça MB, Haddad AN (2023) A systematic review on rainfall thresholds for landslides occurrence. Heliyon 3(10):e23247. https://doi.org/10.1016/j.heliyon.2023.e23247

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity-duration control of shallow landslides and debris flows: an update. Landslides 5:3–17. https://doi.org/10.1007/s10346-007-0112-1

Guzzetti F, Mondini AC, Cardinali M, Fiorucci F, Santangelo M, Chang K-T (2012) Landslide inventory maps: New tools for an old problem. Earth-Science Reviews 112:42-66. https://doi.org/10.1016/j.earscirev.2012.02.001

Guzzetti F, Gariano SL, Peruccacci S, Brunetti MT, Marchesini I, Rossi M, Melillo M (2020) Geographical landslide early warning systems. Earth-Science Reviews 200:102973. https://doi.org/10.1016/j.earscirev.2019.102973

Guzzetti F, Gariano SL, Peruccacci S, Brunetti MT, Melillo M (2022) Rainfall and landslide initiation. In Morbidelli R (Ed.) Rainfall - Modeling, Measurement and Applications, Elsevier, pp. 427-450. https://doi.org/10.1016/B978-0-12-822544-8.00012-3

Hausfather Z, Peters GP (2020) Emissions – the ‘business as usual’ story is misleading. Nature 577:618-620. https://doi.org/10.1038/d41586-020-00177-3

Herrera G, Mateos RM, García-Davalillo JC, Grandjean G, Poyiadji E, Maftei R, Filipciuc T-C, Jemec Auflic M, Jež J, Podolszki L, Trigila A, Iadanza C, Raetzo H, Kociu A, Przyłucka MKułak M, Sheehy M, Pellicer XM, McKeown C, Ryan G, Kopacckovà V, Frei M, Kuhn D, Hermanns RL, Koulermou N, Smith CA, Engdahl M, Buxó P, Gonzalez M, Dashwood C, Reeves H, Cigna F, Lišcák P, Pauditš P, Mikulenas V, Demir V, Raha M, Quental L, Sandic C, Fusi B, Jensen OA (2018) Landslide databases in the Geological Surveys of Europe. Landslides 15:359–379. https://doi.org/10.1007/s10346-017-0902-z

IPCC (2023) Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647

Jakob M (2022) Landslides in a changing climate. In: Davies T, Rosser N, Shroder F (Eds.) Landslide Hazards and Disasters Series, Second Edition 505–579. https://doi.org/10.1016/B978-0-12-818464-6.00003-2

Lonigro T, Gentile F, Polemio M (2017) The influence of climate variability and land use variations on the occurrence of landslide events (Subappennino Dauno, Southern Italy). Italian Journal of Engineering Geology and Environment, 85–92. https://doi.org/10.4408/IJEGE.2017-01.S-08

Melillo M, Brunetti MT, Peruccacci S, Gariano SL, Roccati A, Guzzetti F (2018) A tool for the automatic calculation of rainfall thresholds for landslide occurrence. Environmental Modelling & Software 105:230–243. https://doi.org/10.1016/j.envsoft.2018.03.024

Pasini A, Mastrojeni G, Tubiello FN (2018) Climate actions in a changing world. The Anthropocene Review 5(3):237-241. https://doi.org/10.1177/2053019618794213

Persichillo MG, Bordoni M, Meisina C (2017) The role of land use changes in the distribution of shallow landslides. Science of the Total Environment 574:924–937. https://doi.org/10.1016/j.scitotenv.2016.09.125

Peruccacci S, Brunetti MT, Luciani S, Vennari C, Guzzetti F (2012) Lithological and seasonal control of rainfall thresholds for the possible initiation of landslides in central Italy. Geomorphology 139-140:79–90. https://doi.org/10.1016/j.geomorph.2011.10.005

Peruccacci S, Brunetti MT, Gariano SL, Melillo M, Rossi M, Guzzetti F (2017) Rainfall thresholds for possible landslide occurrence in Italy. Geomorphology 290:39–57. https://doi.org/10.1016/j.geomorph.2017.03.031

Peruccacci S, Gariano SL, Melillo M, Solimano M, Guzzetti F, Brunetti MT (2023) The ITAlian rainfall-induced LandslIdes CAtalogue, an extensive and accurate spatio-temporal catalogue of rainfall-induced landslides in Italy. Earth System Science Data 15:2863–2877. https://doi.org/10.5194/essd-15-2863-2023

Picarelli L, Comegna L, Gariano SL, Guzzetti F, Mercogliano P, Rianna G, Santini M, Tommasi P (2016) Potential climate changes in Italy and consequences on land stability, in Ho K, Lacasse S, Picarelli L (eds) Slope Safety Preparedness for Impact of Climate Change, pp. 151-198, CRC press, ISBN 9781138032309

Piciullo L, Calvello M, Cepeda JM (2018) Territorial early warning systems for rainfall-induced landslides. Earth-Science Reviews 179:228–247. https://doi.org/10.1016/j.earscirev.2018.02.013

Pisano L, Zumpano V, Malek Z, Rosskopf CM, Parise M (2017) Variations in the susceptibility to landslides, as a consequence of land cover changes: A look to the past, and another towards the future. Science of the Total Environment 601–602:1147–1159. https://doi.org/10.1016/j.scitotenv.2017.05.231

Reichenbach P, Busca C, Mondini AC, Rossi M (2014) The influence of land use change on landslide susceptibility zonation: the Briga catchment test site (Messina, Italy). Environmental Management 54:1372–1384. https://doi.org/10.1007/s00267-014-0357-0

Reichenbach P, Rossi M, Malamud BD, Mihir M, Guzzetti F (2018) A review of statistically-based landslide susceptibility models. Earth-Science Reviews 180:60–91. https://doi.org/10.1016/j.earscirev.2018.03.001

Rianna G, Zollo AL, Tommasi P, Paciucci M, Comegna L, Mercogliano P (2014) Evaluation of the effects of climate changes on landslide activity of Orvieto clayey slope. Procedia Earth and Planetary Science 9:54–63. http://dx.doi.org/10.1016/j.proeps.2014.06.017

Rianna G, Reder A, Mercogliano P, Pagano L (2017) Evaluation of variations in frequency of landslide events affecting pyroclastic covers in Campania region under the effect of climate changes. Hydrology 4(3):34. https://doi.org/10.3390/hydrology4030034

Rianna G, Reder A, Pagano L, Mercogliano P (2020) Assessing Future Variations in Landslide Occurrence Due to Climate Changes: Insights from an Italian Test Case. In: Calvetti F, Cotecchia F, Galli A, Jommi C (eds) Geotechnical Research for Land Protection and Development. CNRIG 2019. Lecture Notes in Civil Engineering, vol 40. Springer, Cham. https://doi.org/10.1007/978-3-030-21359-6_27

Romeo S, D’Angiò D, Fraccica A, Licata V, Chiessi V, Amanti M, Bonasera M (2023) Investigation and preliminary assessment of the Casamicciola landslide in the island of Ischia (Italy) on November 26, 2022. Landslides 20:1265–1276. https://doi.org/10.1007/s10346-023-02064-0

Sangelantoni L, Gioia E, Marincioni F (2018) Impact of climate change on landslides frequency: the Esino river basin case study (Central Italy). Natural Hazards 93:849–884. https://doi.org/10.1007/s11069-018-3328-6

Santini M, Valentini R (2011) Predicting hot-spots of land use changes in Italy by ensemble forecasting. Regional Environmental Change 11:483–502. https://doi.org/10.1007/s10113-010-0157-x

Scoccimarro E, Gualdi S, Bellucci A, Zampieri M, Navarra A (2016) Heavy precipitation events over the Euro-Mediterranean region in a warmer climate: results from CMIP5 models. Regional Environmental Change 16:595–602. http://dx.doi.org/10.1007/s10113-014-0712-y

Segoni S, Piciullo L, Gariano SL (2018). A review of the recent literature on rainfall thresholds for landslide occurrence. Landslides 15:1483–1501. https://doi.org/10.1007/s10346-018-0966-4

Sidle RC, Ochiai H (2006) Landslides: Processes, Prediction, and Land Use. In: Water Resources Monograpy Series 18. AGU, Washington, DC. https://doi.org/10.1029/WM018