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A systematic review on rainfall thresholds for landslides occurrence

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ABSTRACT

The study of rainfall thresholds is vital in understanding the factors that trigger landslides, being one of the criteria applied to landslide early warning systems that aim to mitigate their consequences. These thresholds enable the prediction of landslide occurrences as a function of rainfall measurements. This work presents an overview of the parameters involved in defining rainfall thresholds based on scientific articles published between 2008 and 2021 that discuss the subject through statistical or physical methods. These articles provided data such as publication information, threshold types, details on the data used in the works, methodology, and application of the threshold in early warning systems. There was a significant increase in research papers on this theme during this period, possibly due to the strategies advocated by the Sendai Framework. However, some regions of the world severely affected by landslides are barely mentioned in these studies. The results indicate specific trends, such as those found in the methods used to define rainfall thresholds and the parameters relating to the database when a statistical approach was used. Certain deficiencies were found, such as those concerning geological-geotechnical conditions for categorizing thresholds, the time scales of rainfall data, rain gauge density, and the criteria to define the accumulated rainfall period to be considered.

1. Introduction

Landslides are phenomena that occur on slopes when they become unstable due to the synergistic effect of specific conditioning factors, also called preparatory variables, such as those relating to geology, soil, topography, and vegetation, with external agents known as dynamic triggering factors such as rain, snow, earthquakes, and human intervention [1,2]. Human occupation of slope areas can contribute to instability due to changes in drainage, ground overload, deforestation, topography alteration, inadequate sewage discharge, and garbage disposal on the surface [3,4]. Besides contributing to slope instability, human presence can lead to risky situations once they are the ones exposed to the landslide hazard [4–7].

Despite recent advances in monitoring, landslide-related disasters, in parallel with greater urbanization, continue to increase [8–10]. Regardless of investments in engineering solutions, the increased frequency, magnitude, and territorial extension of landslide disasters suggest that reducing risk requires not just structural actions but also non-structural measures for vulnerability reduction. Sendai Framework [11], which states that global exposure is growing faster than the reduction of vulnerabilities, has contributed to

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highlighting the necessity of focusing on the reduction of vulnerabilities.

Understanding and defining parameters to evaluate the probability of landslide occurrence is essential to provide a more effective response to landslide disasters. These parameters include soil moisture [11–13], soil movement [14,15], temperature [16,17], and pluviometry [6,18–20]. One of the main purposes of defining these parameters is to assist in early warning systems. These systems are based on measurements of physical parameters that indicate when there is a high probability of landslide occurrence to alert the agencies and the population with sufficient antecedency to coordinate an appropriate response, thereby reducing the social and economic impacts of disasters. The use of warning systems for landslide risk reduction has been studied all over the world, proving to be a viable preventative measure in dealing with severe impacts on the human population [3,21–23], especially when considering the high costs and low sustainability involved in structural measures [24], as well as the time required to implement them.

Regarding rain-induced landslides, the most commonly used variable for early warning systems is rainfall, which can be measured or estimated by rain gauges [23,25] or weather forecasts via satellite or radars [21,26]. Certain authors consider rainfall indirectly by measuring specific parameters related to the presence of water in the soil [27–29]. Some works also consider the combination of more than one parameter, such as rainfall and temperature [30,31].

The rainfall value above which there is a high probability of landslide occurrence is called rainfall threshold. The first works concerning rainfall threshold for landslides were published in the 1970s, most notably the articles of Onodera et al. [32], who studied landslides triggered by rains in Japan; Lumb [33], in Hong Kong; Nilsen and Turner [34], in urban areas of California (United States); Campbell [35], also in California; Guidicini and Iwasa [36] in the tropical environment of south-eastern Brazil, and Caine [37], who tested a statistical model globally valid, using landslides of different locations. More recently, the study of Guzzetti et al. [38] presented a thorough review concerning intensity-duration thresholds, which became a milestone in the field of rainfall thresholds for the triggering of landslides. This article initiated a significant increase in scientific published research into rainfall thresholds throughout the world. Another factor that may have intensified studies on thresholds in this period is the launch of the Hyogo Framework for Action [39], the most important instrument at the global level for the implementation of disaster risk reduction, which highlighted among its priorities the importance of using early warning systems.

Rainfall thresholds can be developed using both physically-based methods involving hydrogeological and deterministic models, referred to as physically based in this work [13,40–42], and statistical methods, based on the observation of historical time series of rainfall and landslides [22,31,43,44]. Some works use both physical and statistical methods [45,46].

The definition of rainfall thresholds by statistical methods is generally a function of two rainfall parameters, which can be basically of four types: a) intensity-duration (ID), which considers the duration and intensity of a rain event [20,26,47]; b) accumulated rainfall (AR), which considers one or more periods of accumulated rainfall [44,48,49]; c) event-duration of rain (ED) [19,50,51]; and d) event-intensity (IE) [52], where event refers to the accumulated rainfall in the rain event. Among the accumulated rainfall type of rainfall threshold, some studies consider only one period of accumulated rainfall, and some consider two periods or more. For this reason, the rainfall threshold values can refer to the immediately preceding rain, i.e., as the landslide trigger, or to two distinct rain periods, the first related to the preparatory rain and the second to the triggering rain (Table 1).

Several factors may influence the rainfall threshold estimation for a given location, namely: characteristics of rainfall data (monitored period, frequency of measurements, and spatial distribution of data), local physical aspects, and the choice of the analysis method itself. Given the variation of these factors, there is a diversity of procedures and parameters in the literature for estimating rainfall thresholds.

Along with the increase in the published research, several deficiencies in rain threshold definitions have become apparent due to a lack of data, lack of data reliability (date and/or time of the event, problems in rain gauges measurements, inaccuracy, representativeness of rainfall for the studied area), and use of inappropriate methods to correlate rainfall with landslides. Guzzetti et al. [53] highlight errors and uncertainties concerning the time of day as well as the date itself of landslides and rain. Segoni et al. [54] draw attention to issues surrounding the validation of the threshold, the criteria for rain gauge selection, the rain gauge density, and the size of the landslide database. The problem with early warning systems is that a high degree of inaccuracy makes people doubt the system, especially the exposed population, thus compromising the effectiveness of their participation in the emergency evacuation of hazardous areas.

The advanced and diverse nature of scientific publications on this subject has led us to investigate the varying characteristics of the data and methods used in these works, aiming to identify possible trends, innovative approaches, and gaps to be filled.

This work aims to review the studies on estimating rainfall thresholds for triggering landslides, make a bibliometric profile considering different aspects of the publication of the article and the methodology adopted, and then discuss the results. Specifically referring to articles that use a statistical methodology to propose rainfall thresholds, this work groups articles according to several aspects explored by its methodology, such as temporal resolution and period of observation, to elucidate the variety and preferences used by the articles. Bringing a more specific focus, this work aims to analyze the methods used to determine the periods of

Table 1
Rainfall measurements used in thresholds.

Parameter	Intensity (I)	Event (E)	Duration (D)	Accumulated rainfall (AR) – one rainfall period	Accumulated rainfall (AR) – two rainfall periods
Triggering rainfall	x	x	x	x	x
Preparatory rainfall					x

accumulated rainfall for which the rainfall thresholds are defined, the relationship of these periods to geological-geotechnical aspects, and the categorization of thresholds according to the physical characteristics of the studied environment. For this review, the collated information covered the following.

- Spatio-temporal distribution of analyzed publications
- Location and extension of the studied region and density of rain gauges;
- Methodology for determining rainfall thresholds;
- Landslide data: observation time, number and magnitude of landslides, determination of the time of landslide occurrence.
- Rain data: rainfall measurement frequency.
- Type of threshold: quantity and duration of rainfall periods considered; use of another parameter in addition to rain.

The data analyzed and summarized in this article can be found in the supplementary information file.

2. Geological-geotechnical conditioning factors of rainfall-induced landslides

The location and time a landslide will occur are the most important questions regarding its forecast. The geological-geotechnical conditioning of a location in association with climate factors defines the time in which a given rainfall triggers the occurrence of landslides [17,55], as well as the type of sliding mechanism that is expected [56]. Therefore, rainfall thresholds may vary from one location to another depending on physical conditions [36,57–59], such as.

a) Soil characteristics and properties - Minerals, texture, compactness, stress history, permeability, and characteristic curve (saturation x suction) condition the shear strength parameters (cohesion and friction angle), pore pressure, and the specific weight of the soil.
b) Slope - The geometry of the slope affects the components of shear stress and normal stress and, consequently, the shear strength mobilized in the soil mass.
c) Geological faults - The presence and characteristics of geological structures influence landslides [60,61]. Fractures can become groundwater flow channels from recharge sites to the rock permeable layer exfiltration place [62], affecting pore pressures in the soil mass in the overlying soil mass as well as within the rock fractures. These factors can induce shallow landslides [63]. The strength parameters of geological discontinuities and their geometric characteristics also affect the location of the critical failure surface.
d) Thickness of the soil layer above the rock - Shallow landslides, with up to 2 m of soil thickness [60,64] refer to thin layers of soil above the rock, or a material more resistant (or even less permeable). In both cases, the landslides occur when there are intense short-duration rains or less intense but more prolonged-duration rains [65].
e) Vegetation cover - The presence of vegetation affects the shear strength of soil in different ways [66]. For example, in the reinforcement and anchoring effects provided by roots [61,62]; the increase or decrease in soil moisture; overloading, and also the transmission of wind forces to the ground layer.
f) Land occupation by humans – Anthropogenic actions are responsible for a significant change in the natural conditions of a slope. Excavation, cuttings, embankments, excess weight, and water flow modifications can significantly decrease the stability of a slope [56,62] by increasing the shear stress and/or reducing the shear strength.

Some studies have evidenced certain types of landslides triggered after different rain patterns (Table 2), characterizing them by intensity and/or duration. High-intensity rains, even of short duration, are associated with shallow landslides [56,65], whereas more complex landslides are linked to soil erosion and flood situations [56]. The flow of debris from shallow landslides can be observed in situations of intense rain, especially if prolonged [60,67]. Debris flow can also occur due to prolonged rains of low intensity when there are high indices of subsurface percolation flow [62]. Long-term rains can also cause shallow landslides due to the exfiltration of permeable rock following rain [63] or deeper landslides in thicker soil layers [56].

The accumulated rainfall before the landslide is important because the most intense rainfall, or that which occurs immediately before the slope failure, is not usually the only cause of the landslide [62,63,67]. The previous rainfall can contribute to increasing the soil moisture condition which, in turn, influences the additional amount of infiltrated water required to trigger landslides [6]. On the

Table 2
Typical landslide patterns associated with rainfall characteristics.

Duration	Intensity	
	High	Low
Short	Shallow landslides [56,65] Complex landslides linked to erosion and floods [56]	There is no evidence that low-intensity rain of short duration can trigger landslides.
Long	Shallow landslides [56] Debris flow after shallow landslides [60,67]. Shallow landslides related to the exfiltration of permeable rock [63]	Debris flow related to subsurface percolation [62] Shallow landslides related to the exfiltration of permeable rock [63] Deep landslides in thicker soil layers [56]

other hand, when geology and morphology aspects allow groundwater percolation through permeable discontinuities in rocks, the time until slope failure, counted from when the rain starts, is not necessarily related to the time that the soil mass needs to reach a specific saturation degree, but rather it relates to the time it takes the water to percolate, through the discontinuities, from higher to lower regions of the slope where the landslide will occur [63,64]. Observing previous soil moisture content shows the influence of seasonality on the presence of water in the soil, demonstrating that the length of rain time needed to provoke soil failure is longer in drier periods than in wet periods [6,60]. In respect of humid regions, where rainfall is better distributed throughout the year, preceding rainfall has less influence on the occurrence of landslides [6].

Given the above, it is clear that local physical characteristics influence not only the values of rainfall thresholds but also the degree of importance of the preceding rain and its duration, in addition to the triggering rain. Therefore, it is expected that the literature

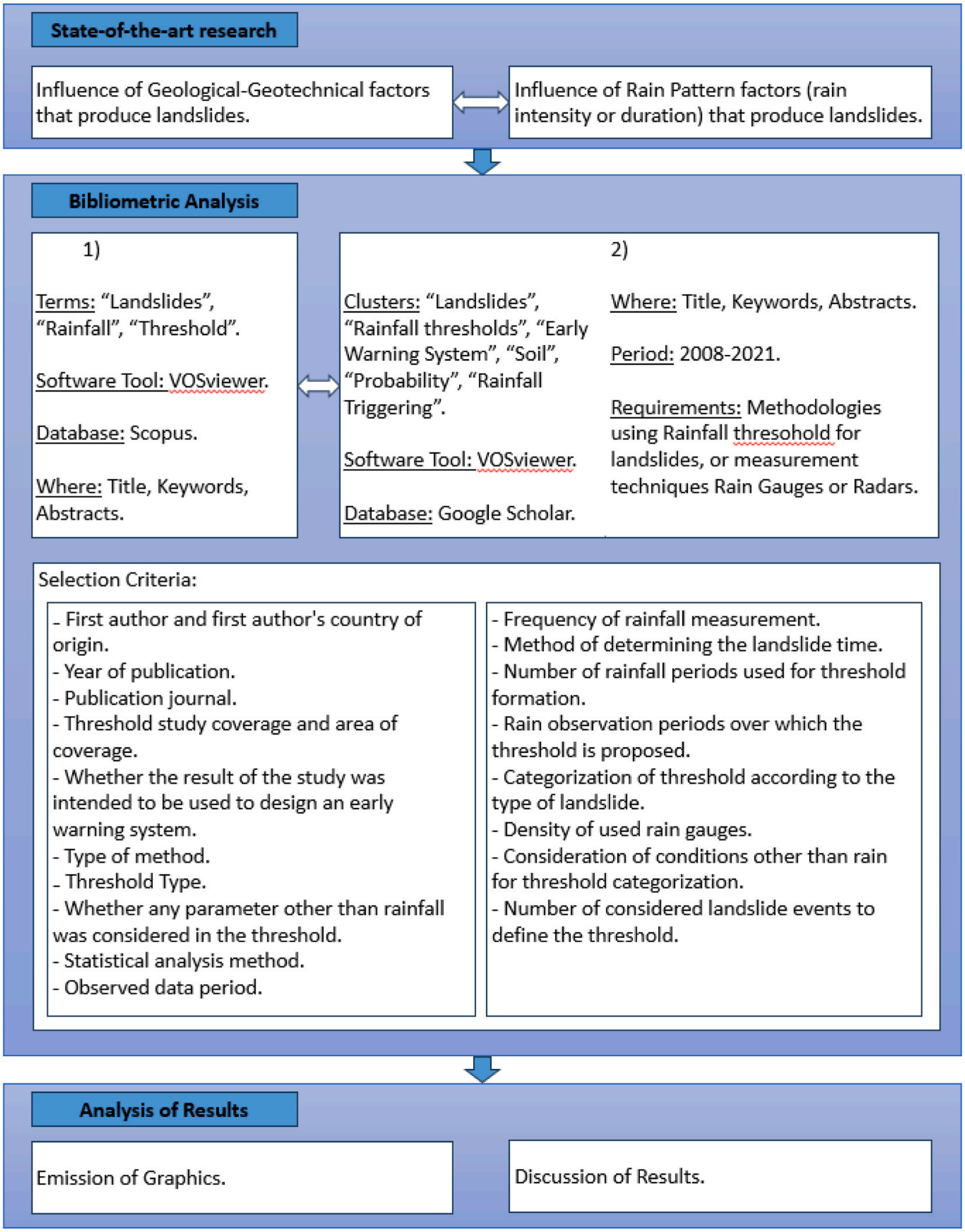

Fig. 1. Flowchart presenting the development of the research.

presents a wide range of calculation procedures and parameters for defining rainfall thresholds. It is important to have prior knowledge of these methods and the geomechanical processes involved in anticipating landslides when defining rainfall thresholds for a given territory to achieve a more accurate representation.

3. Methodology

A noteworthy review on rainfall threshold for landslides was published in 2018 by Segoni et al. [54], presenting statistical-based thresholds from articles collated over 9 years between 2008 (the year of the Guzzeti et al. paper) and 2016. The article by Guzzetti et al. [38], in turn, represented a landmark in publications on rainfall thresholds for landslides, defining terminologies and taking a comprehensive overview of what had been published up to that date, remaining the most cited work in the field. In 2008, there was a marked increase in the frequency of publications on the subject, probably due to the positive effect of the Hyogo Framework for Action [39], which, in 2005, recommended early warning systems as a priority action for disaster risk reduction.

The intervening years since the Segoni et al. paper have seen a significant increase in the rate of scientific research on the subject, which led to the decision to conduct the present investigation. The type of research was exploratory, based on a bibliographic survey, and with a time frame from January 2008 to December 2021 applied to the search for publications. The initial year of 2008 was chosen, as it was the year the article by Guzzetti et al. [38] was published. Some topics were selected and surveyed in this work covering the period 2008–2021 (14 years, inclusive), and certain results were compared with those presented by Segoni et al. [54] from 2008 to 2016 (9 years), which assessed possible changes. As described below, other information was explored with no comparison to the previous review, aiming to characterize and analyze the content of the articles published over these fourteen years.

The selection of the articles that constituted the data source for the analyses in this paper is divided into two stages, and a general flowchart can be seen in Fig. 1.

First, a bibliometric analysis was performed using the Scopus database, looking for articles that contained the set of words "landslide", "rainfall" and "threshold" in the title, keywords, or abstract, for the formation of word clusters, which would then be used to direct the final search of articles to be included in the survey. The VOSviewer software was used to obtain the word cluster graph, highlighting the most relevant terms. The search for papers that contained proposals for rain thresholds was carried out using Google Scholar, considering scientific articles in English that contained the most relevant words obtained in the previous step. Searches for articles containing these terms were also conducted in journals published by Elsevier, Springer, Taylor & Francis, Willey Library, and MDPI. From the results found, only articles that proposed some methodology for defining the rainfall threshold for landslides for a specific area and were based on measurements by rain gauges or radar were selected.

The following information was obtained from each article.

- First author and first author's country of origin
- Year of publication
- Publication journal
- Threshold study coverage (national, regional, or local) and area (km^2) of coverage.
- Whether the result of the study was intended to be used to design an early warning system.
- Type of method for defining the proposed threshold (physical or statistical)

Additionally, for statistical rainfall thresholds.

- Threshold Type (ID, ED, IE, AR, or variations)
- Whether any parameter other than rainfall was considered in the threshold (weather forecast, soil water reading, etc.)
- Statistical analysis method (correlation, regression, Bayesian, etc.)
- Observed data period
- Frequency of rainfall measurement (daily, hourly, etc.)
- Method of determining the landslide time (real-time or temporal approximation).
- Number of rainfall periods used for threshold formation (one, two, or more)
- Rain observation periods over which the threshold is proposed (e.g., 1h and 24h)
- Categorization of threshold according to the type of landslide
- Density of used rain gauges
- Consideration of conditions other than rain (geological aspects, relief, seasonality, etc.) for threshold categorization
- the number of considered landslide events to define the threshold.

4. Results and discussion

4.1. Cluster of keywords

In the search carried out on the works indexed to Scopus, 766 articles were found with the words "landslide", "rainfall" and "threshold" in the title, keywords, or abstracts, published in the period analyzed (2008–2021). Fig. 2 presents a cluster of words formed from the keywords, title, and abstract of the articles, highlighting the terms that appear at least ten times (excluding countries, cities, or regions). The greater the number of times the terns are quoted, the greater the size of the letters. Four main clusters were automatically identified by VOSviewer: the red cluster indicating the implementation of actions related to warning systems and rainfall; the blue cluster showing the physical aspects of mass movements; the green cluster indicating the typology of mass movements and other disaster-related phenomena; and the yellow cluster which brings together themes related to hazard, risk, and vulnerability assessment. The results show the extent of the achievement of the research. Based on the results, the words considered the most relevant to be used for the next phase of the survey were: "landslide", "rainfall threshold", "early warning system", "soil", "probability" and "rainfall triggering".

4.2. Bibliometric analysis of the articles

Using the most relevant words from the cluster, 225 articles published between 2008 and 2021 were found to contain proposals for rainfall thresholds and were then put forward for analysis.

Segoni et al. [54] looked at 107 papers between 2008 and 2016, whereas the present work contemplated 100 articles for the same period. This slight difference may be due to different search methods.

Fig. 3 shows the distribution of article publications and landslide disasters from 2008 to 2021. For articles, we considered the year they were accepted. The distribution of the articles shows an increase per year since 2008 (the first year researched). Comparing the periods 2008–2016 and 2017–2021, we can see a publication rate of 11.1 and 25.2 articles/year, respectively, representing an increase of 127 %. This may be due to the increase in population density in urban areas, meaning that more people are at risk [10], as well as climate change which results in a greater frequency and intensity of the type of heavy rain events that cause landslides [68]. In addition to scientific advances in this area, the strategies advocated by the Sendai Framework focusing on disaster preparedness for effective response may also have influenced research. Taking into consideration the entire period (2008–2021), landslide (which includes landslide, mudslide, and rockfall) disaster distribution per year, according to data from EM-DAT [69], shows an overall decreasing trend, while research into rainfall threshold showed an increasing trend.

Fig. 4 shows the distribution of all 225 articles by country, showing the country of the first author of the work. This graph highlights articles from Italy and China, with 25.8 % and 17.8 % of the publications, respectively. Although headed by a European country, Asia is the continent with the most countries represented. (Fig. 5).

Group 1 contains the variety of countries from where the first author originates and with only one article: Austria, Hong Kong, Ireland, Malawi, Mexico, Russia, South Africa, Sri Lanka, Vietnam, Bangladesh, France, Norway, Thailand, Iran, and the Czech Republic. Group 2 contains the countries from where the first author originates and with two articles: Belgium, Bhutan, Indonesia, Australia, Brazil, Greece, Nederland, Portugal, and Sweden. Group 3 has the countries from where the first author originates and

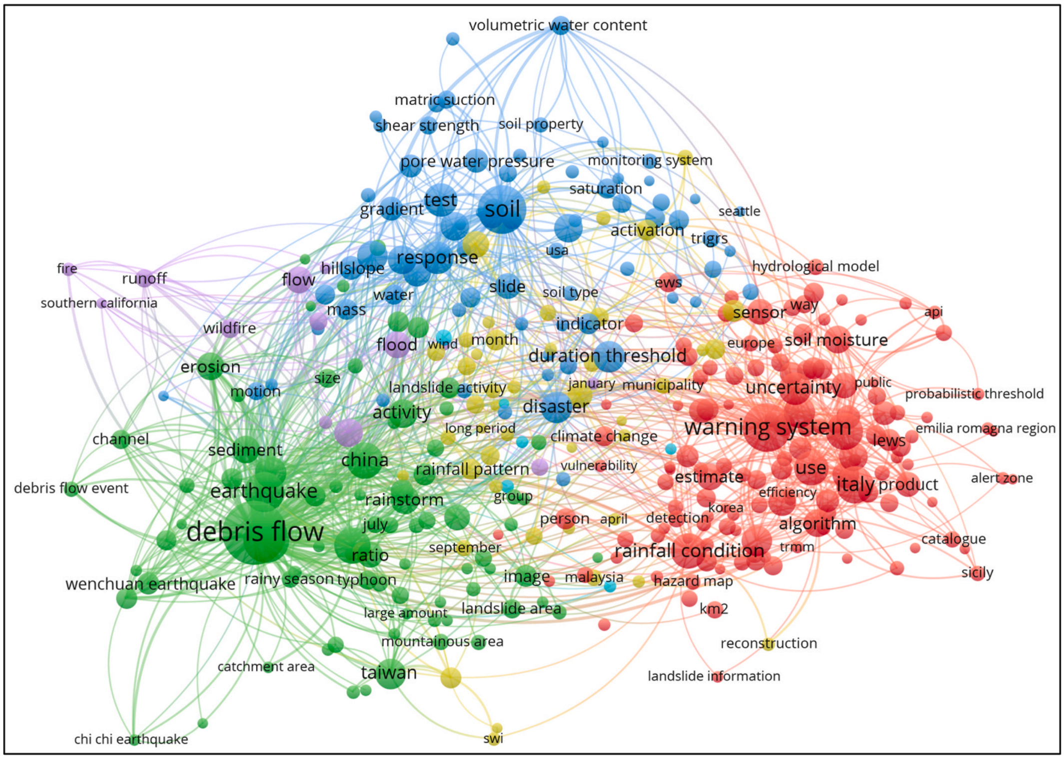

Fig. 2. Word cluster of works from the Scopus database that contained the set of words "landslide", "rainfall" and "threshold" in the title, keywords, or abstract from 2008 to 2021. The size of the word letter indicates the frequency the word is quoted, whereas the colors represent the type of word cluster group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

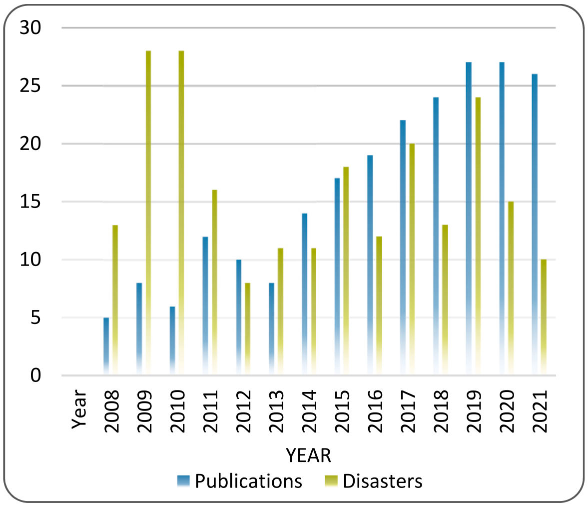

Fig. 3. Distribution of articles and landslide disasters per year between 2009 and 2021.

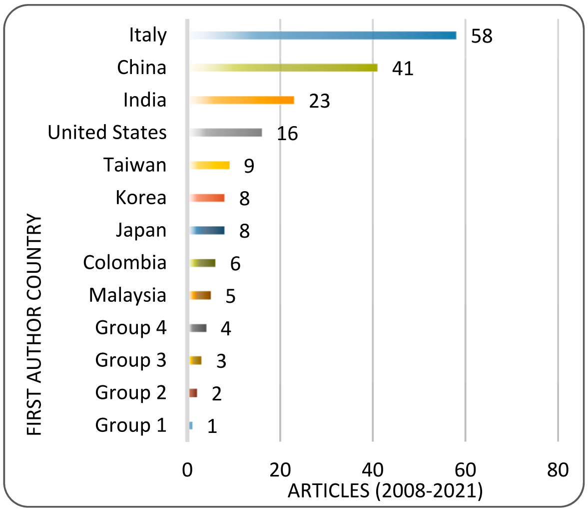

Fig. 4. Distribution of articles by country of origin of the first author.

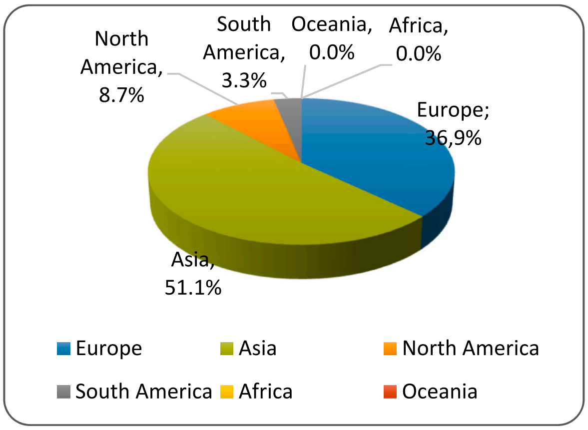

Fig. 5. Distribution of articles by continent of the first author (2008–2021).

contains three articles: Germany and Spain. Group 4 includes the country of origin of the first author and where four papers were published: England, Slovenia, and Switzerland.

The research found 65 different journals where the papers were published. 23 journals have more than one paper published, representing 80.9 % of the total articles. 50.7 % of articles were published in the first five journals, with 28.0 % concentrated in the first two. The 19.1 % of articles categorized as "others" were published in journals on geosciences, engineering, hydrology, climate, remote sensing, computational modeling, risks, and disasters (Fig. 6). It is worth noting the presence of a set of journals, although small in number, that, based on their reach, may indicate a more widespread use of modern tools, such as geomatics, computational modeling, and remote sensing, in approaching the issue.

4.3. Research into methods used to determine rainfall thresholds

4.3.1. Study scope

The proportion of study sites by country and continent, the size of the study area, and the coverage considered in the rainfall thresholds were analyzed. In respect of spatial scale, the thresholds were categorized into.

- Global: when a threshold applies to all areas of the globe [70,71]. A threshold that can be applied anywhere in the world is generic and, by definition, imprecise as it does not consider the many significant physical (natural and anthropogenic) differences that exist, even at a regional level.
- National: when the threshold applies to an entire country or at least a large proportion of it [53]. As explained above, this type of threshold may also not be representative.
- Regional: when the area for the defined threshold includes one or more cities. This area must be reasonably homogeneous for the system to be representative [72]. The analysis will be even more representative if the regional area is subdivided into regions with shared characteristics such as hydrographic basin [23], geological unity [73], and land use [74], yielding specific thresholds for each subdivided area.

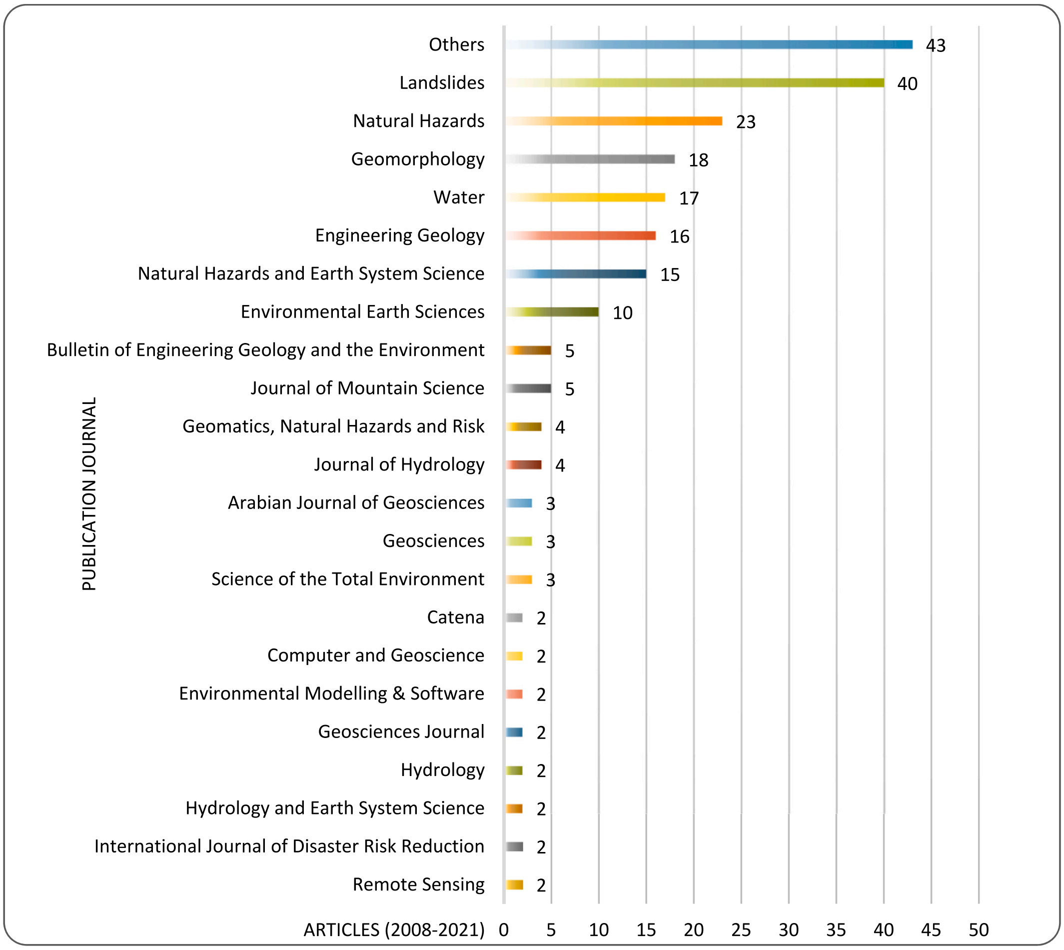

Fig. 6. distribution of articles according to the journals most used.

- Roads and railway: a threshold that considers a stretch of railway or road to which the study is applied [75,76].
- Local: when the threshold is directed to a specific point or a slope [77,78].

Fig. 7 shows the number of studies for each territorial category of the thresholds between 2008 and 2021. The largest number of articles deals with rainfall thresholds for regional study areas (81.2 %) [79–86], while 14.4 % are for local study areas [87–94] and 10.4 % are national thresholds [95–97]. This may be because it is more appropriate to set rainfall thresholds for smaller, reasonably homogeneous areas and more feasible when applied to early warning systems.

The distribution of articles by countries and continents where study areas were located (Figs. 8 and 9, respectively) shows that 50.7 % refers to regions in Asia, with few cases in Africa and Oceania. During the 2008–2021 period, the countries most studied were Italy [98–104] and China [105–111], an observation also seen by Segoni et al. [54] for the 2008–2016 period. Fig. 10 represents these numbers through a distribution map, according to the number of works about landslide occurrence in each country.

Analysis indicates a significant concentration of studies in Europe (especially in Italy), although the number has been growing outside Europe in recent years, mainly in Asia. According to data from EM-DAT [69], between 2008 and 2021, most disasters associated with landslides (including landslide, mudslide, and rockfall) occurred in Asia (59.5 %), followed by Africa (15.9 %) and South America (14.5 %) (Table 3). It can be seen, therefore, that this type of research has seen little development in certain areas, even if those areas have suffered a significant amount of disasters in the last two decades.

4.3.2. *Early warning system*

Although the ultimate purpose of landslide threshold studies is its practical application in early warning systems, some are designed for academic purposes only, for which the objective is to contribute to understanding the geomechanical landslide process and its modeling. Some studies, either because of a lack of data or their inherent unreliability, are restricted to the preliminary construction of warning systems [145,146]. Regarding the purpose of the research, this study shows that almost 70 % of the studies do not explicitly mention the intention for their findings to be applied to an early warning system [147–155], and 32.9 % intend to be part of the development of an early warning system [156–160] (Fig. 11).

4.3.3. *Types of thresholds*

The present work only considered rainfall thresholds based on a physical [161–169] or statistical [170–174] model or a hybrid application of these two methods [175–179]. The distribution of the surveyed works shows that 69.3 % used statistical methods and 20.9 % used physical models to propose rainfall thresholds (Fig. 12). This result may indicate more feasibility of statistical methods as 69.3 % of the works deal with rainfall thresholds for regional study areas (see Fig. 6) when usually there are insufficient parameters for applying a physical method.

26 articles used statistical or hybrid methods based on rainfall measurements [180,181](11.6 % of the total articles researched), and the proposal was to combine these articles with other factors to define the thresholds. These additional factors were.

a) Soil water - This factor includes different measurements related to the water in the soil, such as pore pressure, water table, and subsurface water flow monitoring. These values are used as a pre-conditioning factor related to the presence of water in the soil before the event of rainfall [11,30,182]. It is also worth mentioning that the methodology that combines rain measurements with soil moisturize is known as a hydro-meteorological approach [183].
b) Rainfall forecast - These thresholds [184–186] consider rainfall forecasts using meteorological data from satellite measurements. Usually adopted by locations with a low quantity of rain gauge as a complement to rainfall measurement.
c) Temperature - Bíl and Müller [124], Brigandì et al. [187], and Ponziani et al. [188] mentioned that temperature could be a factor that contributes to rainfall occurrence.
d) Displacement - Badoux et al. [189] and Abraham et al. [190] consider soil displacement measures using local monitoring instruments (e.g., inclinometer). Displacement is a significant indicator of low slope stability safety.

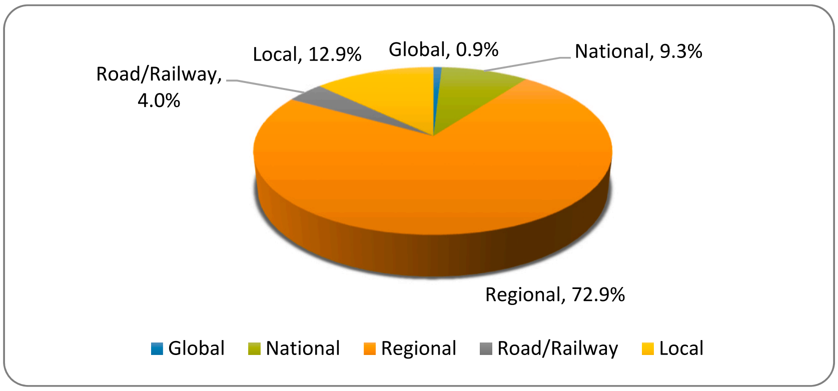

Fig. 7. Distribution of articles by territorial coverage of thresholds (2008–2021).

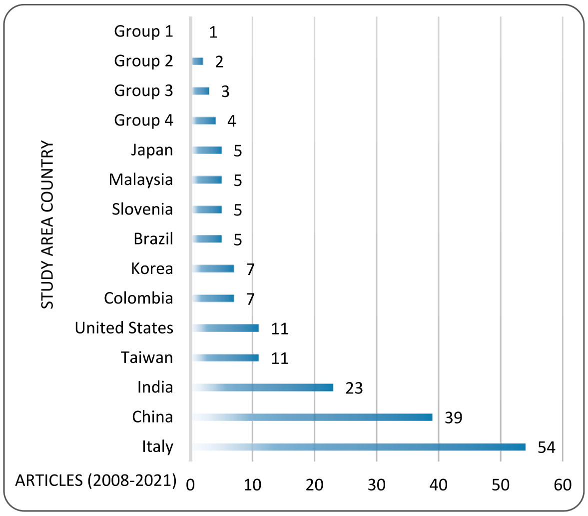

Fig. 8. Distribution of articles by country in the study area. Group 1 contains the countries in which the studied area is located in only one article: Hong Kong [112], Ireland [113], New Zealand [29], Saudi Arabia [114], Serbia [115], Sri Lanka [116], Rwanda [117], East African Rift, Russia [118], Kyrgyzstan and Tajikistan [119], Turkey [74], Iran [120], Papua New Guinea [121], Thailand [122], Jamaica [123], El Salvador [12], and Czech Republic [124]; Group 2 contains the countries in which the studied area is located in two articles: France [125], Honduras [126], Portugal [127], Mexico [128], Philippines [129], Greece [130,131], and Central America [132]; Group 3 contains the countries in which the studied area is located in three articles: Indonesia [133,134], Bangladesh [135,136], Spain [137,138] and Switzerland [139,140], and Group 4 the countries in which the studied area is located in four articles: Vietnam [141,142] and Bhutan [143,144].

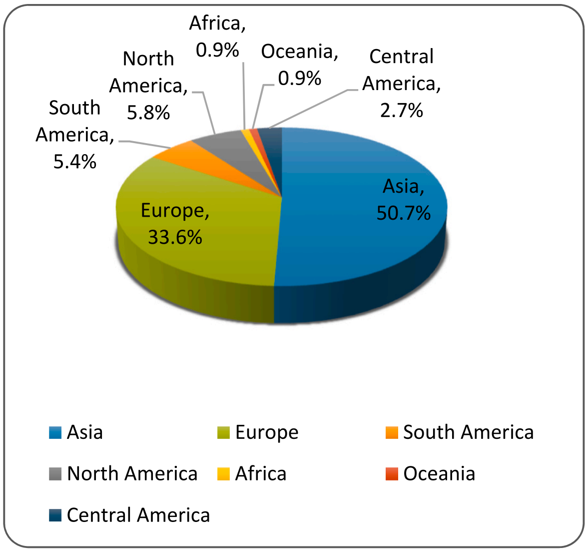

Fig. 9. Distribution of articles in the study area by continent (2008–2021).

e) Snowmelt - This threshold also considers that in temperate regions, landslide sometimes occurs due to snowmelt, where melted water increases pore pressure and the loss of shear strength. However, snowmelt is a slower process and may be considered more of a preparatory factor [191].

These additional triggering factors considered in the statistical thresholds are shown in Fig. 13. Different measurements of soil water are the most common parameters, combined with rainfall thresholds, and are present in 15 statistical threshold articles [106, 192–195], or 59.3 % of the articles that took additional factors into account.

4.3.4. *Thresholds based on statistical methods*

Of the 225 rainfall threshold papers, 178 are based on statistical (or physical and statistical) methods from the 2008–2021 time frame. It is worth noting that 98 articles, more than half of this group, were published after the Segoni et al. [54] review, i.e., between

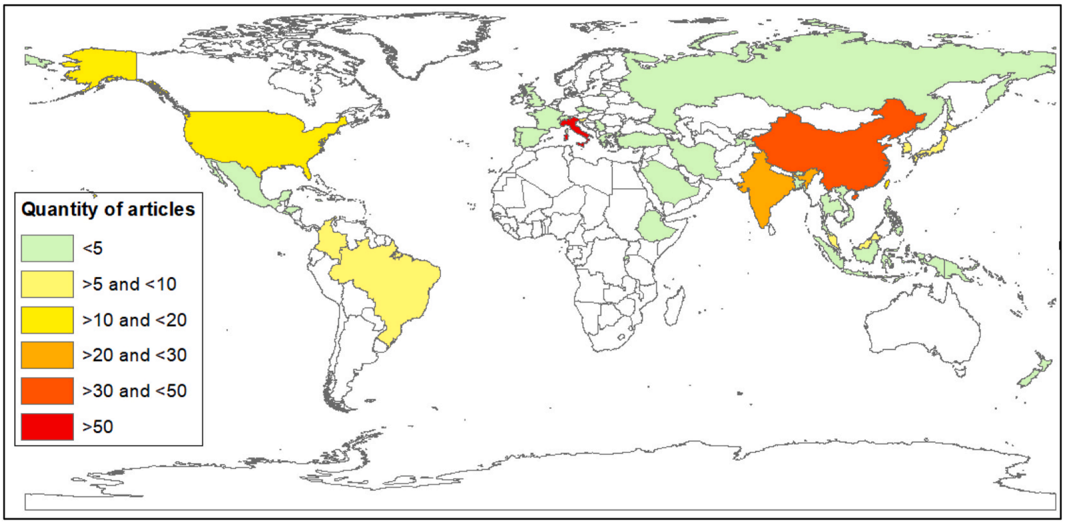

Fig. 10. Quantity of articles in which the study area belongs in each country territory (2008–2021).

Table 3
of disasters associated with landslides across continents between 2008 and 2021 compared to the number of case studies found in this survey.

Continent	Percentage of disasters (2008–2021)	Case studies (2008–2021)
South America	14.5 %	5.4 %
North America	0.9 %	5.8 %
Central America	4.8 %	2.7 %
Africa	15.9 %	0.9 %
Asia	59.5 %	50.7 %
Europe	2.2 %	33.6 %
Oceania	2.2 %	0.9 %

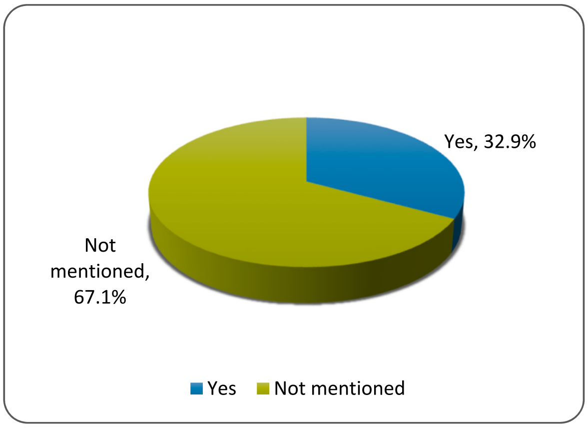

Fig. 11. Distribution of articles by the intention of the threshold proposed by the work to be applied to an early warning system (2008–2021).

2017 and 2021, which indicates a significant advance in scientific publications on this kind of method to define the thresholds. The following topics explore methodology characteristics from the perspective of only statistical threshold articles.

Article distribution was explored according to rainfall parameters established in the analyses, namely: ID [196–200], IE [119,201,202], ED [203–205], and AR [206–209], as presented in Section 1. Among the works that used accumulated rainfall (AR), some only used one rainfall period, while others used two. Of the thresholds that used two rainfall periods, one of them was usually the event rainfall or the event rainfall day in the case of daily measurements. The second rainfall period may be temporally located before the first rainfall period, identified only as the antecedent rainfall or the second rainfall period may overlap the first one.

Some works use modified versions of the previously presented parameters: Rainfall Intensity only (I) [179] and Rainfall Duration

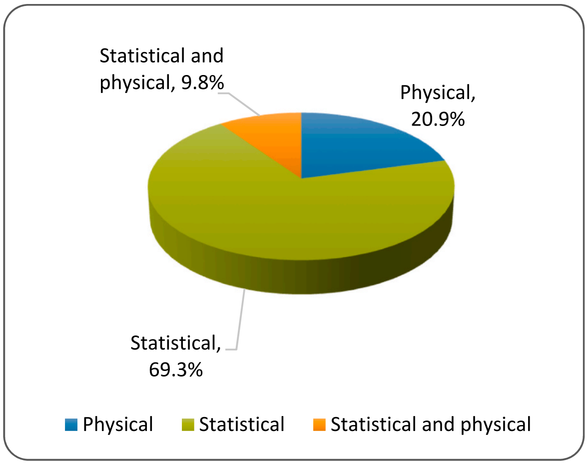

Fig. 12. Distribution of articles by methods used to define rainfall thresholds (2008–2021).

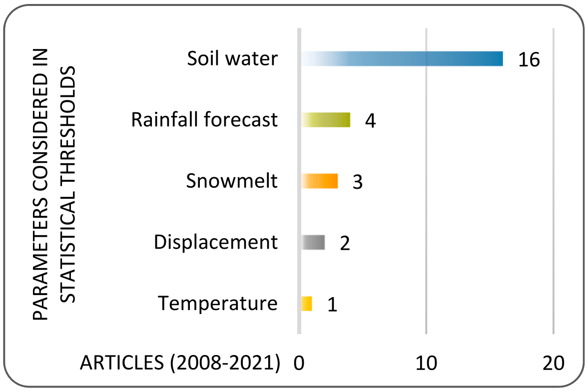

Fig. 13. Distribution of articles by additional factors for the formation of statistical rainfall thresholds.

only (D) [90]. In addition, some articles use more than one method for comparison purposes or apply a different method just to validate or calibrate the system. The distribution of articles by type of parameter considered appropriate for the statistically-based rainfall threshold is presented in Fig. 13. AR is the most significantly used parameter type, followed by ID and ED. Segoni et al. [54], on the other hand, found that ID was the most used parameter type to define rainfall thresholds. Fig. 14 summarizes the information about types of thresholds and their frequency.

To determine the thresholds, a large group of different statistical methods is used to study the correlation between rainfall data, landslide events, and other triggering factors. For classification purposes, statistical methods were subdivided into seven subgroups: numerical models (similarly, interactive interpolations) [210–213]; statistical models [214–217]; machine learning [218,219];

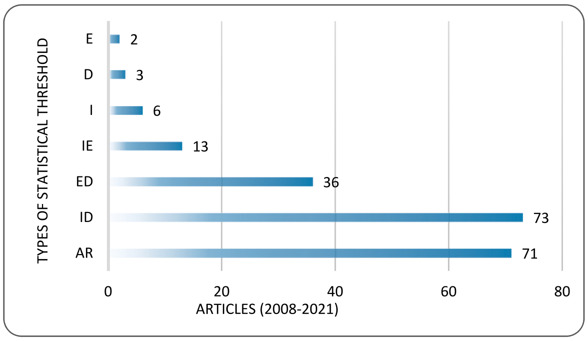

Fig. 14. Distribution of articles according to rainfall parameters used in the analysis by the statistical method (E-event rain, D-duration of the rain, I-intensity of rain, IE-intensity and event rain, AR-accumulated rainfall, ED-event and duration, ID-intensity and duration).

decision algorithms [119,220,221]; multi-criteria analysis [222–225]; regression models [75,205,226–228], and quantile analysis methods [229,230]. Although only two works analyze the rainfall and landslide occurrence data using machine learning in the 2008–2021 period, as it is a method that has been developed in various science fields, it is expected that more works using this type of methodology will be developed in the future. The distribution of the 178 articles using the statistical approach to define the threshold is shown in Fig. 15.

It is worth mentioning that an important aspect of methodologies development is performance analysis. Out of 178 statistical thresholds articles, 102 present some validation process [75,100,124,174]. Most of them (44) reported testing a group of events, distinct from the events used for the threshold development, in the same methodology for calibration and/or validation of the model [186,231–233]. 38 works presented some analysis of performance, as the metrics obtained from the Receiver Operating Characteristics (or the Area Under the Curve) [234,235], or methods that use confusion matrix analysis of True Positives, False Positives, True negatives, and False Negatives from testing events in the model [115,236].

Performance analysis is also a tool that can enlighten the uncertainty attached to the model. According to Nikolopoulus [237], rainfall threshold development accumulates a series of errors, since the variability of rains [237,238], the errors committed in the measurement can be increased by large spatial variability. Small database of events [239], the lack of knowledge of the time that landslide occurred [238], and may also increase the uncertainty of thresholds. False alarm ratio is the main consequence attached to rainfall thresholds, and it can be controlled with the validation of the model.

4.3.5. Data characteristics and approach to historical time series analysis

In this analysis, specific historical time series were analyzed, such as the data observation period, quantity of landslide events, the temporal resolution of rainfall measurement, density of rain gauges, and information about the definition of the time of landslide occurrence.

a) Observation period

Thresholds based on statistical methods depend on the amount of data to be statistically representative and require a long period of quality data to achieve a consistent result. The time series adopted for rainfall varies in the case studies being researched and is longer in sites that regularly practice rain monitoring and landslide registration. Fig. 16 summarizes the distribution of articles over a range of years. Of 178 articles that use statistical methods, 43 % used a database of 10 years or less [186,240–244].

b) Quantity of landslide events

As per the measurement of observation time frames, it is essential to know the number of landslide events considered appropriate in defining the statistical threshold. As shown in Fig. 17, 29 % of the 178 articles that apply statistical methods use 50 events or less [245–249]. The total number of landslides, nevertheless, must also be analyzed considering the total area of study, as a great number of landslides may be insufficient to represent an area if this area is too extensive.

Attention should be given to the high number of studies based on either a relatively short period of data collation (up to 5 years), which normally limits the set of pluviometry scenarios, or a small number of landslides (up to 50), which may compromise the reliability of the results. With these cases, even if the results are relevant, the rainfall thresholds established should be considered preliminary. It is also worth mentioning that the statistical use of less than 100 landslide events increases the uncertainty of the threshold [250].

c) Temporal resolution of rainfall measurement

The temporal resolution, also known as 'revisit time', is important in associating the correct volume of rainfall with a landslide. The most common temporal resolution considered in the articles researched is daily (57.9 %) [193,251–254], followed by hourly in 53 articles (29.8 %) [195,255,256] (Fig. 18). Segoni et al. [54] stated that 52.2 % of papers published in 2008–2016 considered hourly

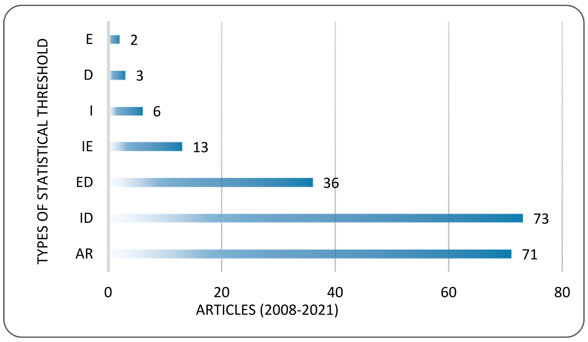

Fig. 15. Distribution of articles by statistical methods used to define rainfall thresholds.

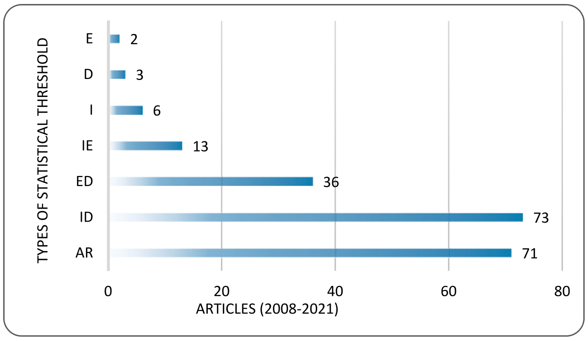

Fig. 16. Distribution of articles by ranges of observation periods.

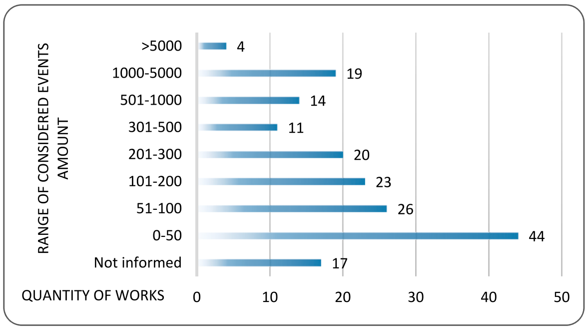

Fig. 17. Distribution of articles by range of quantity of landslide events.

rainfall measurements, whereas 39.1 % used daily measurements. It suggests that the progress witnessed, in terms of scientific publications, was not linked to improved temporal resolution.

d) Density of rain gauges

The number of rain gauges per area is another important parameter to indicate the extent to which the rainfall data collected is representative of the studied area since rainfall varies spatially according to local meteorological and physiographic characteristics [257]. Among other results for the distribution of studies by rain gauge density, it was found that the percentage of studies using less than 10 rain gauges per 100 km^2 [258–262] is 35.2 % (Fig. 19). According to Segoni et al. [54], in the period 2008–2016 only 7.9 % of the articles mentioned less than 10 rain gauges per 100 km^2 and 46.5 % more than 50, which may indicate a decrease of representativeness.

e) Definition of the time of landslide occurrence.

Recording the date and time of landslide occurrence is important in defining rainfall thresholds. Often the data records may not contain the correct time or even the correct day of the landslide, which can lead to errors in calculating the preceding rainfall. Analysis was carried out as to whether the times of landslide events were known or, for cases in which it was not known if there were any criteria adopted to estimate the time. Fig. 20 shows the distribution of works according to the different procedures used to record the day and time of landslide occurrence. Most of the articles (75.9 % or 132 from a total of 178) do not specify how landslide occurrence time was determined [233,263–266]. 14 present a record of the day and the time in which the landslide occurred [1,2], 12 present only the day [115,267], 11 present criteria to estimate the time occurrence [203,260,268] and finally, 5 have a record of the day and period of occurrence [121,269].

The 11 articles that mentioned a criterion to estimate the time of the landslide occurrence considered that it occurred at.

a) the time of the daily peak of the rainfall (in terms of intensity);
b) the end of the event rainfall;
c) the day before the landslide was registered (with no time specified);
d) 48h after the event rainfall ended;
e) any time within 36h, with a weight of 24/36 for the day of registration and 6/36 on the following day, using a continuous approach of the time of observation;

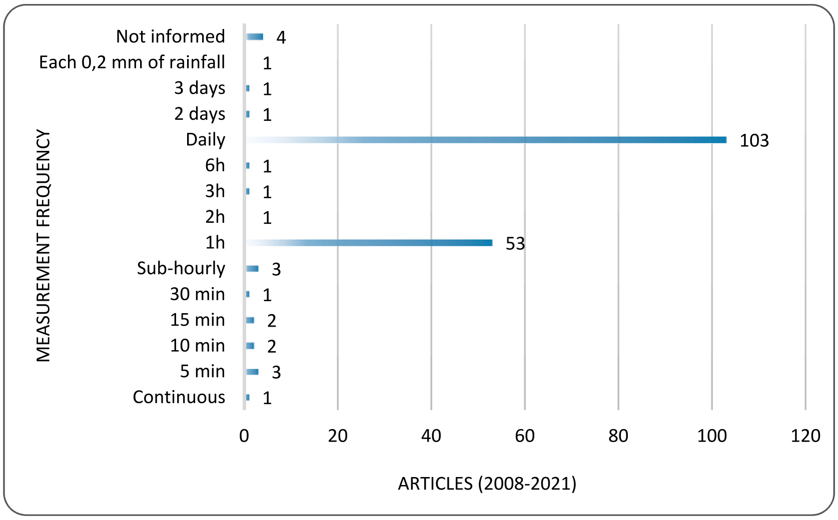

Fig. 18. Distribution of articles by frequency of rainfall measurement.

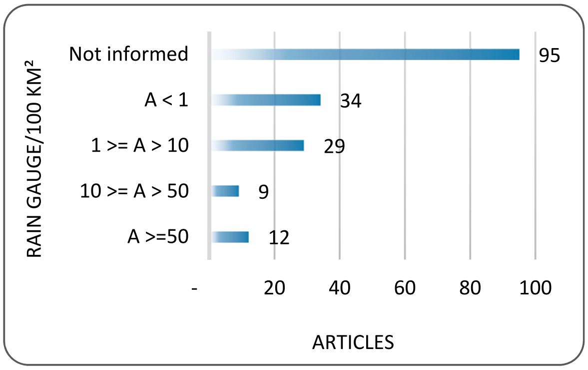

Fig. 19. Distribution of articles by representativeness of rain gauges per area (A = number of rain gauges/100 km^2).

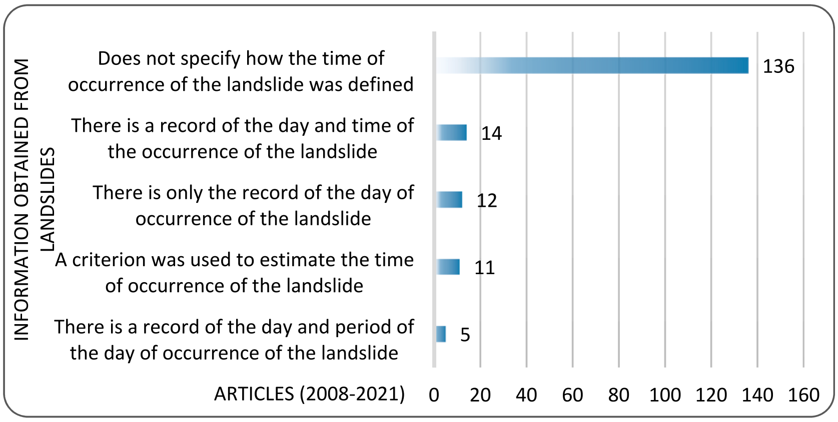

Fig. 20. Distribution of articles according to procedures used to determine landslide occurrence time.

f) 0h (midnight) on the day the landslide was registered.

Fig. 21 presents the distribution of work according to the criterion for estimating the time of occurrence of the landslide. Analyzing the results presented in this section shows inherent limitations in the majority of the scientific papers, as they do not mention the spatial density of the distribution of rain gauges or how the moment of the landslide occurrence was defined. It is also worth mentioning that most studies were based on a daily resolution of rainfall measurements, which is not representative of landslides triggered by short-duration and high-intensity rainfall. Although the majority of studies have been developed recently, it should be noted that most of the works consider a rainfall database of a relatively short period of up to 10 years. There is also the problem, in studies that use the statistical method, of inaccurate registering of the time when the landslide occurred, which compromises the establishment of the relationship between rainfall data and the occurrence of landslides. Some works took the occurrence of the landslide to be at the rainfall peak [112,270], but this procedure needs supporting evidence, as some landslides occur after the peak or even after the rain has finished [271]. We should also mention the work of Peres et al. [47], which analyzes the delays between the time of the actual landslide occurrence and the time it is recorded and proposes strategies to mitigate this uncertainty.

4.3.6. Characteristics considered for the categorization of thresholds

As shown in Section 2, the dependence of the occurrence of landslides on rainfall varies with the type of landslide as well as natural and anthropogenic geological-geotechnical conditioning factors that define landslide susceptibility. These characteristics influence not only the values of rainfall thresholds but also the type of rainfall parameters more associated with landslides and enable the categorization of rainfall thresholds for the same study area. The larger the area considered for defining landslide thresholds, the greater the need for threshold categorization.

Adopting different thresholds that depend on the characteristics of landslides makes it essential to have more reliable values and set specific preparation and response actions for when a landslide disaster becomes imminent. Some articles categorize landslides according to their type, such as a shallow landslide or debris flow, and/or their magnitude, to propose different rainfall thresholds. Of the 178 studies with a statistical threshold, 78 (45.5 %) defined thresholds according to a landslide classification based on their type, magnitude, or both [200,272–275] (Fig. 22). Although a significant number of papers define thresholds for different categories of landslides, 63 % (97) of the articles do not follow this definition, leading to thresholds that are unreliable (See Section 2). In some cases, this categorization may not be feasible because of the limited number of landslide records or the fact that the landslides were not classified when they were registered.

Of the total number of statistical threshold works (178), 59 present a categorization of thresholds according to the physical characteristics of the study area, such as hydrographic basins, geological unit [276], seasonality [269], as well as other characteristics (Fig. 23). Notably, some articles used more than one physical characteristic [101,149]. The division of thresholds in different alert zones is the most common type of categorization, separating the thresholds by areas with specific homogeneities. However, despite the importance of the threshold categorization, this was carried out by only 62 studies [19,204](34.8 %) of the 178 presented in this review.

4.3.7. Accumulated rainfall

a) Quantity of periods of rainfall considered

A further important consideration concerns the number of observation periods of accumulated and/or antecedent rainfall used to compose the threshold. Fig. 24 shows the number of works that composed thresholds based on 1 or 2 observation periods of accumulated precipitation, in which 7 do not provide information about the observed rain periods; 118 (66.3 %) used only one period [199,277–279], and 53 (30.5 %) used two [98,148,170]. This lack of information can result in a deficiency in the threshold, meaning that it may be able to distinguish between preparatory rain and triggering rain. According to Mendonça et al. [49], one unique rainfall observation period may contain a huge variety of landslide occurrence probabilities depending on the secondary rainfall observation period.

b) Period of accumulated rainfall considered

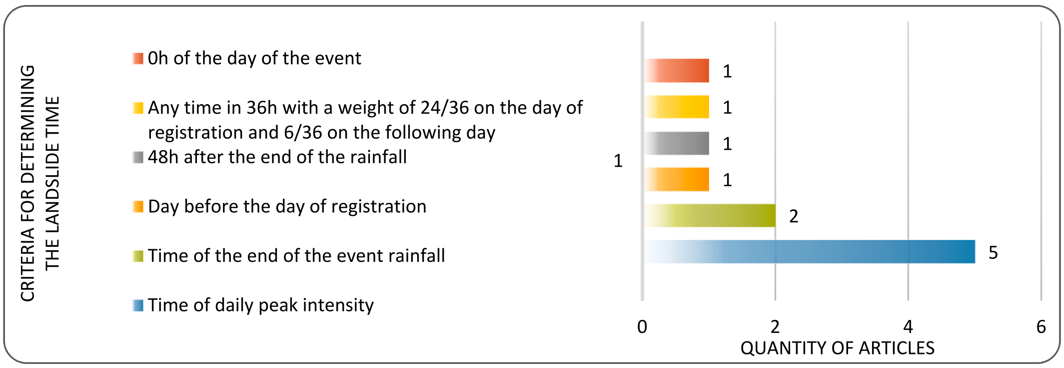

Fig. 21. Distribution of articles by criteria for determining landslide time.

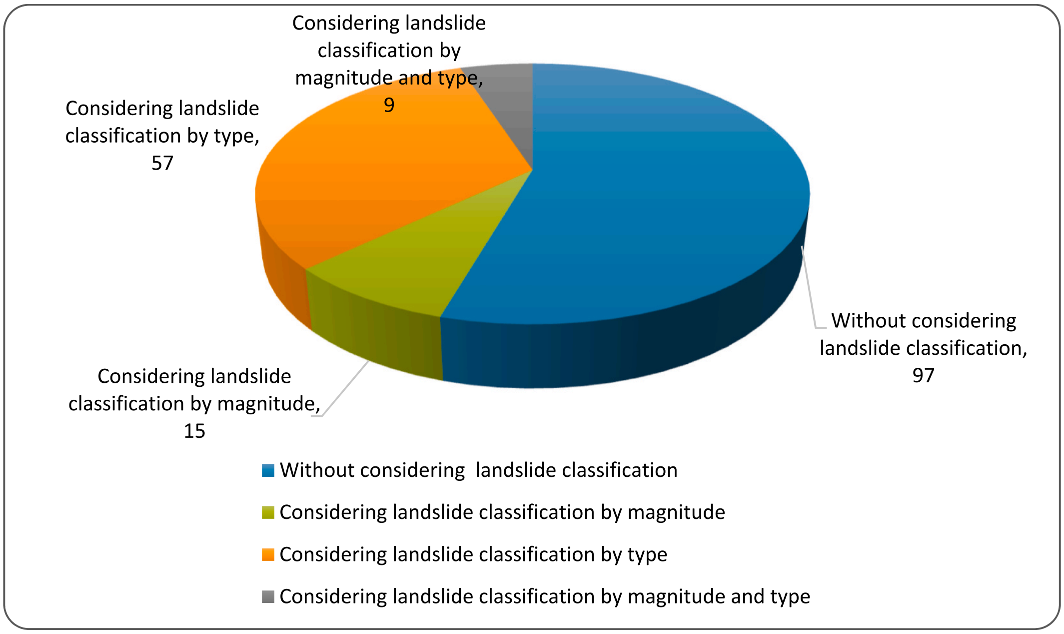

Fig. 22. Distribution of articles by definition of threshold according to landslide classification.

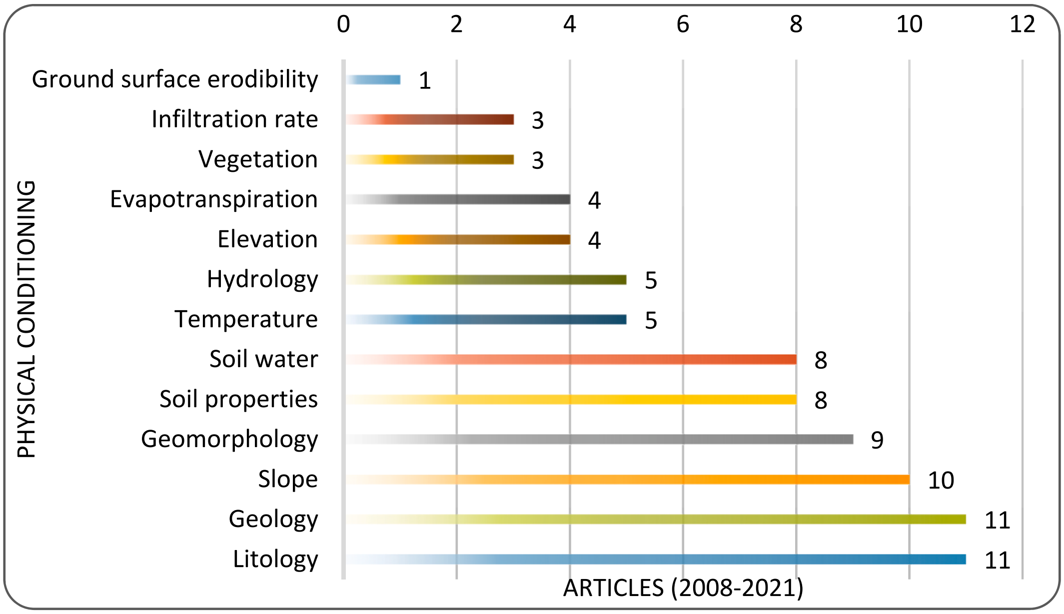

Fig. 23. Distribution of articles by categorization of threshold according to physical characteristics of the locality.

There was a wide variation in the periods for which rainfall is considered to define the thresholds. In areas with a small annual rainfall or during dry periods, rainfall measured over consecutive days is more appropriate. However, in tropical regions, or the wet season, it can rain an enormous amount in a short period, and the pluviometry should be measured in minutes or hours at the most.

The accumulated rainfall threshold may be based on just one or two rainfall periods. Importantly, when only one period is observed, the probability of landslide occurrence varies according to the preceding period. For example, a certain amount of rain in 24 h may not be important when analyzed alone, whereas it may be significant when analyzed with 96 h of accumulated rainfall. Thus, the accumulated rainfall threshold based on two periods of rainfall presents a more precise measurement of probability. In the accumulated rainfall threshold of two periods, the first period is usually shorter and implemented immediately before the landslide event. The second period, usually longer, may be of two types. For the first type (Type A), the second rainfall period overlaps the first one. In the other (Type B), the second rainfall period is located before the first period, and they do not overlap. Fig. 25(a and b) summarizes the

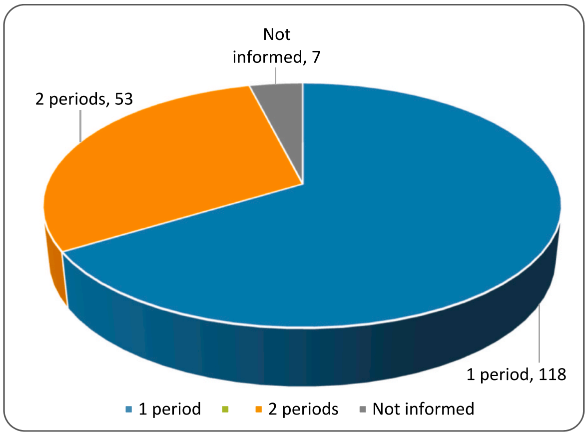

Fig. 24. Distribution of articles by the number of periods adopted in the definition of rainfall thresholds (2008–2021).

temporal location of each type of accumulated rainfall.

Of the 178 total studies that use statistical methods to define thresholds, 115 cite the accumulated rainfall period used to develop the rainfall threshold [90,150,184,280]. Figs. 26 and 27(a,b) show the distribution of articles by range of accumulated rainfall period, in thresholds based on just one period and on two periods. Of the 121 articles with a one-period threshold, 24 (35.3 %) cover a rainfall period of between 6 and 30 days [51,105,106]. The majority of papers that present two rainfall periods, 35 (or 74.5 % of the 50 articles), cover the first period of between 1h and 24h [29,178,222], whereas the most recurrent (28 or 59.6 %) second period is between 6 and 30 days [149,173,280]. The relatively small quantity of studies defining rainfall thresholds for short periods of less than 24h is of concern for landslides triggered by heavy rainfall, concentrated in a few hours, which is typical of tropical regions [281].

A further deficiency in threshold definition is the lack of a criterion for choosing rain periods. It is worth noting that rainfall periods in which landslides are more dependent vary with the geological-geotechnical conditions, as presented in Section 2, yet only 12 (6.7 %) of the 178 statistical threshold articles in this review mentioned having adopted some criterion in choosing periods of rain when defining the rainfall threshold.

5. Conclusions

A literature review on rainfall thresholds for the triggering of landslides, based on 225 articles published between 2008 and 2021, was conducted to characterize the scientific research regarding the methods and data analyzed in these studies. A comparison was made with the benchmark review of Segoni et al. [54] for the period 2008–2016, in the light of a significant increase in scientific publications on this theme in recent years, possibly due to the Sendai Framework for Disaster Risk Reduction 2015–2030 [282], which encouraged this type of study. Considering there are still many challenges to be faced and gaps to be filled in the definition of rainfall thresholds and scientific publications, this article provides an overview of the current trends and the strengths and weaknesses observed in the works reviewed.

Despite this trend toward disseminating research, the institutions where these studies are developed are concentrated in comparatively few countries. Entire continents, such as South America and Africa, seriously affected by landslide disasters, feature

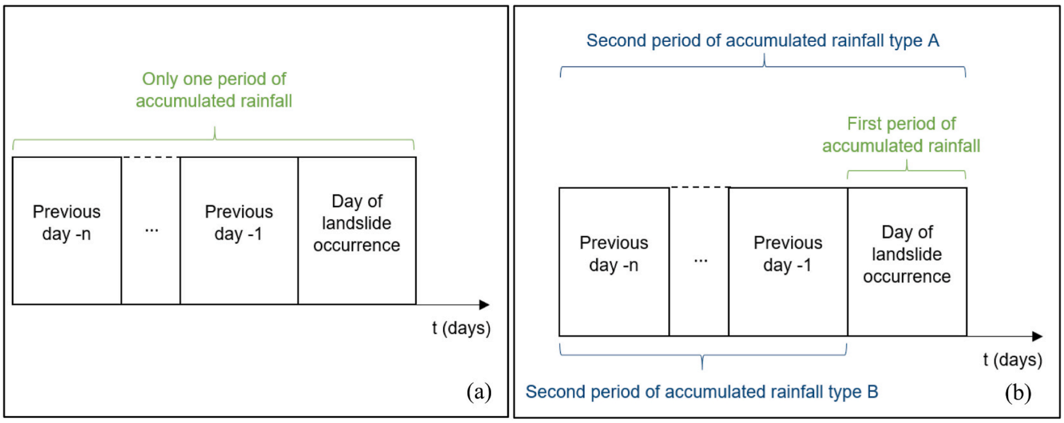

Fig. 25. Types of periods of rainfall in the accumulated rainfall threshold of (a) one period and (b) two periods.

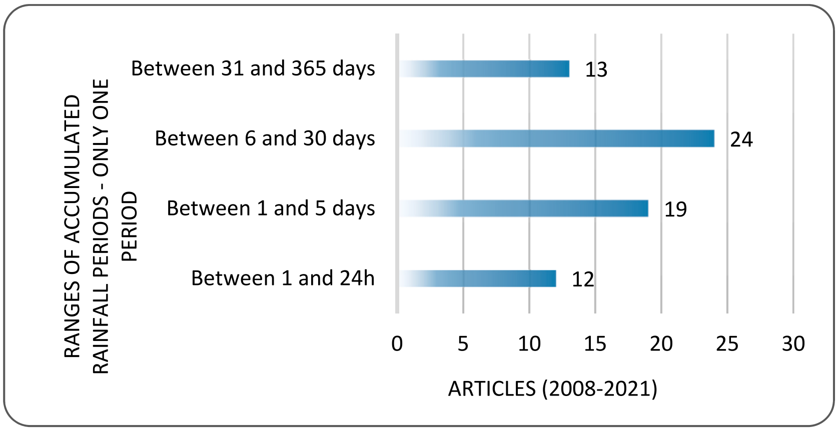

Fig. 26. Distribution of articles by range of accumulated rainfall period, in thresholds based on only one period.

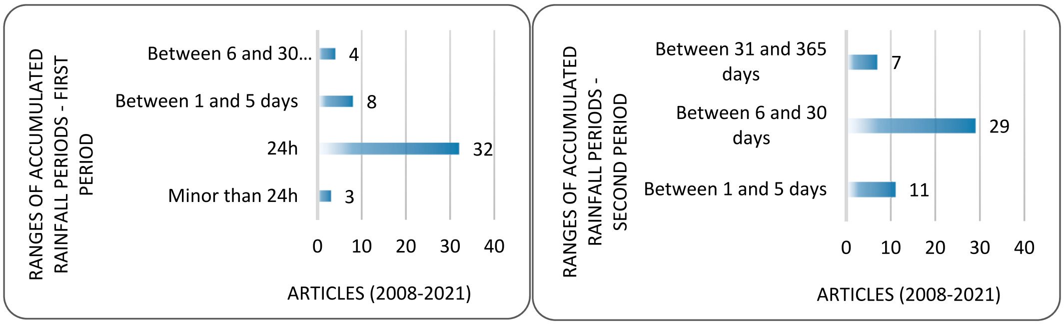

Fig. 27. Distribution of articles by range of accumulated rainfall period, in thresholds based on two periods: (a) first period and (b) second period.

much less in these studies, which may result from a lack of infrastructure and an appropriate environment for research and development in this field.

Regarding the methodologies used to obtain statistical rainfall thresholds, of the 178 statistical thresholds analyzed, more than 50 different methodological procedures were observed. This indicates one of the main findings of this work, which is the lack of standardization in the methodologies adopted to obtain rainfall thresholds. Therefore, an enormous number of works do not present continuity, and the methodology was not deepened. Given that 69.3 % of the studies involved only statistical methods, this further underlines the importance of data quality and management. It is expected that the use of machine learning and a hydro-meteorological approach will be more explored in future works, although these two methodologies were not considerably present in the articles of the 2008–2021 interval.

The main limitation of this work is the difficulty of comparing certain aspects of the methodology. This led to the lack of information about certain aspects of the methodology developed in several articles. Another limitation is the consequence of the small amount of work that analyzes the threshold performance. If it is considered that common thresholds development methods may contain a considerably high uncertainty, which is not taken into account by their respective works, it is presumed that the methodologies discussed in this work only present the state of literature, and not necessarily the evolution of rainfall thresholds towards the best approach. For future research, it is expected more thresholds developed including the step of performance analysis.

There was often a lack of explanation regarding rain gauge density; precision in landslide and rainfall records; time scale of rainfall data; criteria to determine the most relevant period of rainfall; the number of rainfall periods considered; categorization of landslides and site characteristics, all of which serve to define rainfall thresholds.

Despite the observed limitations, this article highlights a significant and growing effort from the scientific community to contribute to landslide disaster risk reduction through advancing studies on rainfall thresholds, which will hopefully be applied to early warning systems. In general, to achieve consistent rainfall thresholds, attention should be paid to investing in a dense and frequent rainfall measurement network, as well as in quality data about landslides and their natural and anthropogenic conditioning factors and careful data management. Also, the analysis should be complemented with some *in situ* monitored parameters, such as water content. In this sense, this work has drawn attention to crucial issues that need to be addressed and paths that should be followed to advance research on the subject.

CRediT authorship contribution statement

Fernanda Cristina Gonçalves Gonzalez: Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Maria do Carmo Reis Cavacanti:** Writing – review & editing, Validation, Software, Methodology. **Wagner Nahas Ribeiro:** , Writing – review & editing, Software, Formal analysis. **Marcos Barreto de Mendonça:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Assed Naked Haddad:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23247.

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