Chapter

Empirical Rainfall Thresholds for Landslide Occurrence in Serra do Mar, Angra dos Reis, Brazil

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Abstract

In the tropical environment such as Brazil, the frequency of rainfall-induced landslides is particularly high because of the rugged terrain, heavy rainfall, increasing urbanization, and the orographic effect of mountain ranges. Since such landslides repeatedly interfere with human activities and infrastructures, improved knowledge related to spatial and temporal prediction of the phenomenon is of interest for risk management. This study is an analysis of empirical rainfall thresholds, which aims to establish local and regional scale correlations between rainfall and the triggering of landslides in Angra dos Reis in the State of Rio de Janeiro. A statistical analysis combining quantile regression and binary logistic regression was performed on 1640 and 526 landslides triggered by daily rainfall over a 6-year period in the municipality and the urban center of Angra dos Reis, in order to establish probabilistic rainfall duration thresholds and assess the role of antecedent rainfall. The results show that the frequency of landslides is highly correlated with rainfall events, and surprisingly the thresholds in dry season are lower than those in wet season. The aspect of the slopes also seems to play an important role as demonstrated by the different thresholds between the southern and northern regions. Finally, the results presented in this study provide new insight into the spatial and temporal dynamics of landslides and rainfall conditions leading to their activation in this tropical and mountainous environment.

Keywords: Landslide, rainfall thresholds, quantile regression, tropical environment, Brazil

1. Introduction

Because of their ability to move rapidly, mobilize large amounts of debris, and initiate spontaneously, landslides pose a threat to people and infrastructure [1, 2]. The danger is heightened by the fact that they can occur in wet or dry regions, and on steep or shallow slopes [3]. Synergistic effects between increasing urbanization, sustained deforestation, and increased rainfall variability caused by climate change portend an increase in the frequency of catastrophic landslides such as that experienced in recent years [4].

In Brazil, as elsewhere, the mechanism of slope saturation by rainwater represents the main cause of landslide triggering [5–7]. Their onset is related to exceptional rainfall events of short duration, such as intense precipitation associated with a thunderstorm, or events of long duration and low intensity [8]. Specifically, high-intensity, short-duration precipitation events are known to trigger shallow landslides [9] - landslides with a failure surface depth of less than two meters [10] - while long duration, low intensity precipitation events generally result in deep seated landslides [11]. However, the causal relationship between rainfall and landslides is not so simple [12]. Rather, their initiation is associated with the infiltration of water into the soil that causes an increase in hydraulic pressure and a decrease in resistance, ultimately leading to failure of the affected surface [13]. The effectiveness of the process therefore depends on the hydraulic, physical and mechanical properties of the terrain, in addition to other factors such as slope steepness, vegetation cover and climatic characteristics [12]. In this regard, mountainous regions are particularly favorable to landslides because of the steep slopes, but especially because of the orographic uplift of humid air masses that cause significant precipitation at high elevations and on slopes exposed to prevailing winds [14, 15].

In the Brazilian municipality of Angra dos Reis, located in the Serra do Mar Mountain Range, heavy summer precipitation has historically triggered several landslides, causing a significant number of casualties and considerable damage, especially in the last decade. As an example, the catastrophic events of December 2002 and January 2010 resulted in 93 casualties, forced the evacuation of more than 2,500 residences and generated economic losses of approximately R$120 million. In this tropical environment, the frequency of rainfall-induced landslides is particularly high due to the rugged terrain, heavy summer rainfall, and improper land use regarding the physical and climatic environment [7]. The risk posed by this geomorphological hazard is particularly high due to the fact that almost 60% of the population lives in slope areas [16] and more than 25% (44,000 inhabitants) live where a high risk of landslides is considered [17].

However, since the beginning of the research on rain-triggered landslides in Brazil, no suitable threshold has been proposed for the Angra dos Reis territory. In fact, the thresholds of Guidicini and Iwasa [18] were established for the whole Serra do Mar, whose area is four times larger than that of Angra dos Reis, while the one elaborated by Soares [19] is not representative of the triggering conditions due to the use of an inadequate database. Thus, despite the recurrence of this natural hazard and the socioeconomic risks it poses, the relationships between rainfall characteristics and landslide occurrence remain poorly studied and partly misunderstood in this rugged region of Southeast Brazil. Therefore, the establishment of rainfall thresholds at local and regional scales is of great interest for the municipality of Angra dos Reis and could be an effective tool of prevention and mitigation in the landslide risk management perspective.

2. Regional setting

2.1 Geological and geomorphological settings

The Brazilian municipality of Angra dos Reis is located in the western part of the state of Rio de Janeiro. It represents an area of 825 km^2 composed of four districts (Angra dos Reis, Cunhambebe, Ilha Grande and Mambucaba) comprising 116 neighborhoods. The urban center of the Angra dos Reis district covers an area of 6.5 km^2, or 0.84% of the territory covered by the Angra dos Reis region, and includes 21 neighborhoods.

The geology is composed of 30% granites, 27% orthogneiss, 33% paragneiss with a minor proportion of contemporary sediments (Neogene-Quaternary). In terms of soils in the area, they are characterized by the presence of rock outcrops, fluvio-marine deposits, colluvium, and saprolites [20]. Superficial saprolites are less than two meters thick, have a large amount of boulders, and are generally located on very steep slopes where bedrock outcrops. The thick saprolites, associated with the upper and lower slopes, are more than two meters thick and result from a significant chemical alteration of the rocks in situ favored by the high heat and humidity.

The western part of the state of Rio de Janeiro belongs to the physiographic region of the Serra do Mar, which extends for just over 1,000,000 km along the southern and southeastern Brazilian coastline [21]. The Serra do Mar originated from tectonic movements that began ~80 million years ago (Late Cretaceous) with epirogenic uplift of the crystalline shield throughout southeastern Brazil [22]. Today, this mountain range forms an enormous tectonic barrier parallel to the coast.

Angra dos Reis is located more precisely in the southern part of the Atlantic Plateau, which corresponds to the Bocaína Plateau region and includes the escarpments of the Serra do Mar and the narrow coastal plain of Ilha Grande Bay. In the Bocaína Plateau, the slopes are moderately inclined (10 to 35°), but can exceed 35° in places. The strong geomorphological activity is visible by landslide scars and scree slopes [23]. The urban center of Angra dos Reis, with a summit at 571 m above sea level and very steep slopes, is part of this geomorphological unit. The area of Ilha Grande Bay with its mountainous massif oriented East–West, which culminates at 1031 m of altitude, is also included in this geomorphological unit. The massif has steep slopes, rocky walls, and well incised river channels [23]. Finally, due to the East–West alignment of the Serra do Mar in this area, the slopes are mainly oriented to the North and South, both regionally and locally.

2.2 Climate and land use

The climate is particularly variable due to the proximity of the Atlantic Ocean and the rugged terrain associated with the Serra do Mar. According to the Köppen-Geiger classification, the region is characterized by an Af-type climate; a humid tropical climate without a well-defined dry season corresponding to average monthly temperatures above 18°C and average monthly rainfall above 60 mm. Annual rainfall varies between 2000 and 2500 mm [24]. Typical of tropical regions, there is heavy rainfall in the summer (December to March; with average rainfall exceeding 250 mm and about 16 rainy days/month) and a period of lesser rainfall in the winter (June to August; with total rainfall around 80 mm and less than 10 rainy days/month) [15, 18]. During the rainy season, which concentrates nearly 60% of the annual precipitation [15], rainfall of 200 to 300 mm in 24 to 48 hours is frequent [5]. This intense rainfall is furthermore largely responsible for the high frequency of landslides in this part of Brazil [7, 25].

The intensity and distribution of precipitation is influenced by various static and dynamic factors [26]. Dynamic factors refer to the different air masses and their circulation patterns such as, among others, frontal systems, the South Atlantic Subtropical Anticyclone and the South Atlantic Convergence Zone. The static factors correspond rather to the geographical location (latitude, maritime proximity that facilitates solar radiation, evaporation and cloud formation) as well as to the topographical characteristics (elevation and perpendicular orientation of the Serra do Mar Mountain Range with respect to atmospheric currents that favor the development of intense thunderstorms through the orographic lifting of polar humid air masses blowing in the northwest direction) [24]. Therefore, coastal areas and windward-facing slopes (south-facing) tend to be wetter (2000-2500 mm/year) due to orographic precipitation, while leeward-facing slopes (north-facing) are generally drier (1400-1700 mm/year) due to moisture loss from advection of air masses over the Mountain Range [27].

The high population growth since the early 1970s in Angra dos Reis, related to the construction of the Governor Mario Covas highway (Br-101) and the Angra 1 and Angra 2 nuclear plants [16], has generated significant pressure on the physical environment. However, the rugged topography (7% plains and 93% hills/mountains), which limits the amount of land available and suitable for human settlement, as well as the lack of land-use planning regulations have caused chaotic development of the territory [28]. This development has led to deforestation, surface sealing, transformation of plateaus into pastures and residential development on steep slopes, generating furthermore an accumulation of waste, a change in natural drainage conditions and anthropic filling and excavation activities that have affected the stability of the slopes and increased the likelihood of landslide occurrence [5]. As a result, the biophysical cover of the municipality of Angra dos Reis, which was once entirely Atlantic Forest (*Mata Atlântica*) in its original state [29], is now much more diverse. Indeed, it is now composed of 86% of secondary Atlantic Forest, with the rest being pastures, urban areas, dunes, mangroves, etc.

3. Data acquisition and methodology

3.1 Landslide database

The landslide inventory includes all the landslides that occurred in the territory of the municipality of Angra dos Reis. The information's included are the geographical coordinates of the landslides and the date of occurrence. However, the inventory does not allow distinguishing between different mass movements (landslide, debris flow, etc.). Therefore, all types of landslides are considered here, without any particular distinction. This is a well-established approach [30, 31] and advantageous considering the fact that the typology of landslides is unknown, unspecified or uncertain since many reports come from citizens, journalists or technicians without adequate scientific training. Duplicate landslides, those with identical geographic coordinates and date of occurrence, were removed from the database. The same is true for cases with erroneous locations. All the recorded landslides were georeferenced and compiled into a geographic database using ArcGIS software [32].

Finally, each of the landslides was associated with a rainfall region according to its location (see Section 3.2), in order to associate or not the cases of landslides with the occurrence of rainfall episodes in the municipality. Subsequently, the landslides were matched to the rainfall data series according to the date of occurrence. This allowed each landslide to be assigned a daily precipitation value (R), 3-, 5-, 10-, 15-, and 30-day antecedent precipitation values, as well as duration (D) and cumulative precipitation values during the rainfall event (E).

3.2 Rainfall analysis

The rainfall data were collected from a regional network consisting of two rain gauges administered by the State Institute of the Environment (SIE) and 19 rain gauges managed by the Civil Defense of Angra dos Reis. In the case of the SIE rain gauges, automatic recordings were made every 15 minutes, 96 times a day. In the case of the rain gauges of the Civil Defense, the data were daily and the reading was done manually every morning at 9:00 am. However, the period covered by the data sets varies considerably depending on the rain gauge station. In order to estimate the amount of rainfall responsible for the occurrence of each of the recorded landslides, the regional study area was first partitioned and an area of influence was calculated for each rainfall station using the Thiessen polygon technique [33] with ArcGIS software [32]. Next, the databases associated with the 21 rainfall stations were agglomerated based on geographic proximity to obtain complete time series for the 6-years period considered.

First, the daily data (R) from each station were associated (or not) with a rainfall event, i.e. a more or less continuous period of rainfall. A rainfall event begins when at least two millimeters of rain have been accumulated in 24 hours and ends at the beginning of a period of at least 24 hours without rainfall. Once the rainfall events were identified, the duration (D) in hours of each episode and the associated total rainfall (E) in millimeters could be calculated. These values were then used to establish thresholds based on the duration of rainfall events (ED).

In a second step, each daily precipitation (R) was associated with antecedent precipitation values. The antecedent precipitation values correspond to the daily totals accumulated over 3, 5, 10, 15 and 30 days before the daily precipitation considered (A (3d), (5d), (10d), (15d), (30d)). These data will allow to evaluate the role of the previous precipitation in the landslide triggering and to determine the most significant previous period.

3.3 Probabilistic rainfall event: duration thresholds (ED) for landslides

The thresholds (ED) were developed from the combination of the variables D and E obtained for each landslide that was triggered during a rainfall event and are defined respectively as the duration (h) and cumulative precipitation (mm) from the start of the rainfall event to the occurrence of the landslide. ED thresholds were developed at the regional and local scales, as well as for the North and South aspects and also for the wet and dry seasons. In the latter case, the considered duration of the dry and wet seasons has been extended to simplify the analyses. Therefore, the dry season is from May to October and the wet season is from November to April.

In all cases, the E (cumulated event rainfall) and D (duration of the rainfall event) values were first plotted in a line graph (log–log coordinates), based on the frequentist method assuming that the threshold curve is a power law such as reported by Guzzetti et al. [34] and Peruccacci et al. [35]:

$$E = \alpha D^{\gamma} \tag{1}$$

where α and γ are the scaling and the shape parameters that control the slope of the power law threshold curve.

The intercept α and the slope γ were then determined through a frequency analysis of the empirical rainfall conditions that have triggered landslides. The large number of landsides recorded over a 6-years period in the study area appears sufficiently complete and representative to determine the 1% and the 5% exceedance probability levels. The mean values of α (intercept) and γ (slope) and their uncertainties ($\Delta\alpha$ and $\Delta\gamma$) were estimated with the non-parametric technique of bootstrapping.

4. Results

4.1 Catalogs of landslides and rainfall events at regional scale

Using the Thiessen polygon technique, six rainfall regions were identified at the regional scale: three in the South (Japuiba, Angra dos Reis, and Jacuecanga – JAJ) and three in the North (Mambucada, Bracui, and Serra d’Agua – MBS). Then, the

	Extent	RE	LE	D (h)			E (mm)		
	(km^2)			Min	Max	Mean	Min	Max	Mean
Municipality	825	484	1640	24	624	101,3	2	542,9	111,9
South: JAJ	374	357	1276	24	624	102,2	2	542,9	112,8
North: MBS	451	127	364	24	432	97,9	2	400,8	108,7
Urban Center	6,5	129	526	24	528	108,4	2	540,5	114,9

Table 1.
Statistics of rainfall events (RE), landslide events (LE), duration (D) and accumulation of rainfall (E) that initiated landslides at the regional scale (municipality, north, south) and local scale of the urban center of Angra dos Reis.

1640 landslides recorded were associated with one of the 1434 rainfall events compiled (≥2 mm). In that regards, only 33% (484 out of 1434) of these rainfall events have triggered landslides (**Table 1**).

A North–South disparity appears in the number of rainfall events recorded in the North (127) and South (357) of the municipality (**Table 1**). The number of recorded landslides is significantly higher in the South (1274) compared to the North (364). Therefore, 78% of the landslides occurred in the South (JAJ) of the region (**Figure 1**), where the majority of the population and urban areas are concentrated. On the other hand, few landslides were recorded in the North (MBS) and in the vegetated areas of the Bocaína Plateau (**Figure 1**).

Regarding the inter-annual variability of rainfall events triggering landslides for the 6-years period analyzed indicates that landslides occur every year. On an intra-annual basis, the average number of triggering events and the ratios of triggering

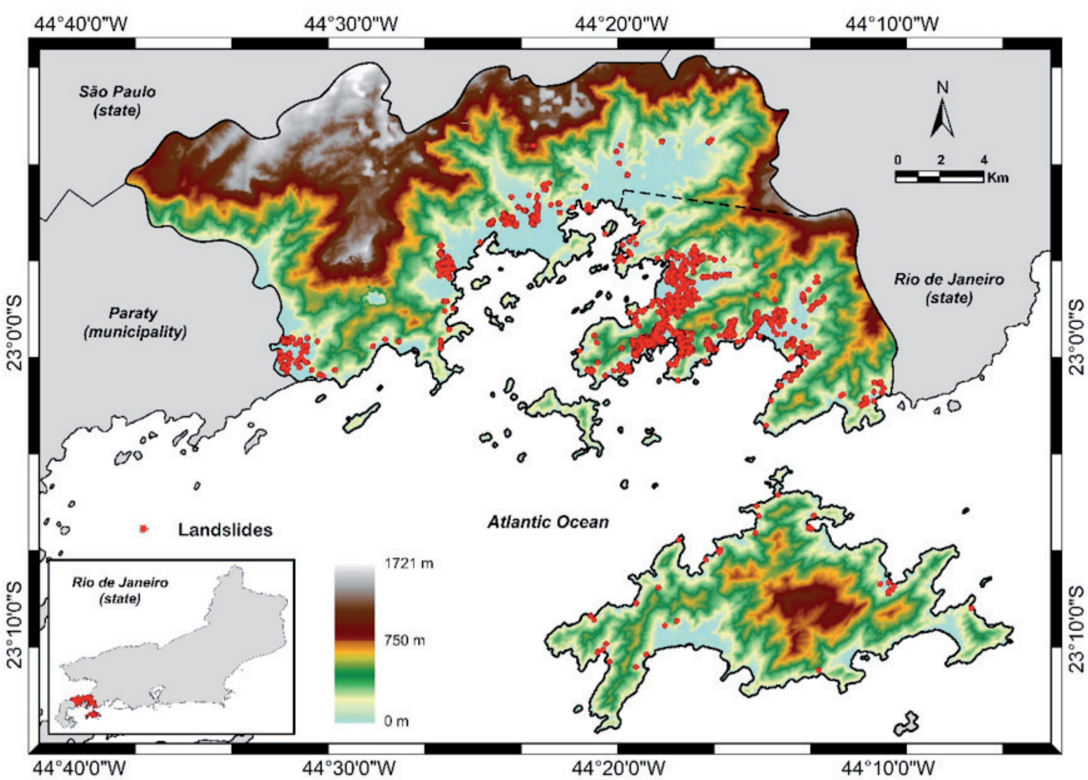

Figure 1.
Map of the study area (825 km²), Municipality of Angra dos Reis in the state of Rio de Janeiro, Brazil. Red dots show location of the 1640 landslides recorded and the black dashed line represents the limit between north (Mambucada, Bracui, and Serra d'Agua – MBS) and south (Japuida, Angra dos Reis, and Jacuecanga – JAJ) regions.

versus non-triggering events vary primarily with the seasonality. Indeed, the average numbers and ratios are 9 and 40% in the wet season (January to April), 5 and 25% in the dry season (May to August), and 8 and 32% in the transition season (September to November).

The 484 rainfall events that likely triggered landslides lasted approximately 4 days (101 hours; **Table 1**), with a minimum and maximum duration of 24 and 624 hours (26 days), and initiated an average of three landslides. Specifically, 45% (219 out of 484) of the triggering events initiated a single slide, 75% (365 out of 484) triggered three or fewer slides, and only 8% (37 out of 484) generated ten or more failures, with a maximum of 38 landslides per episode. In this regard, two rainfall events recorded in the region of Angra dos Reis triggered exactly 38 landslides. The first one started on December 27, 2012 and ended on January 4, 2013, accumulating 540.5 mm of rain in nine days, while the second one started on January 9, 2013 and ended on January 22, 2013 after dumping 372.9 mm in 14 days. While the first of the two rainfall events had accumulated only 46.5 mm in the previous 30 days, the second had accumulated 565 mm of antecedent rainfall over 30 days. Therefore, the soils of the region had received 937.9 mm in 44 days as of January 22, 2013. Angra dos Reis was specifically the region the most affected by landslides during the study period, accounting for 39% (638 out of 1640) of all landslides recorded. This corresponds to an average of four landslides per triggering rainfall event, which is slightly higher than the regional average of three at the municipal level.

On a seasonal basis, 69% of the landslides (1130 of 1640) were initiated during the wet season. This significantly outweighs the amount of landslides that were initiated during the dry season and the transition season, both of which accounted for approximately 15%. On a monthly basis, January had the most landslides initiated, followed by March, April and December in relatively equal proportions. This average of 69 landslides per month in January is almost twice as the amount recorded in the other wet months (December, February, March, and April), which average 33, and five times more than in drier months (May to October), which average 13. Finally, the month of May represents the least likely period for landslide occurrence with only six landslides recorded on average. This data is nevertheless significant and indicates that landslides can occur in any month of the year, despite less precipitation in the winter period (May to August).

With respect to slope steepness, 71% of the cases occurred on gentle slopes (0 to 20°), 27% on slopes between 20 and 35 ° and only 2% on steep slopes (>35 °). Regarding slope orientation, more than a third of the landslides (34%) were initiated on south facing slopes, i.e. facing the prevailing winds, while 24% were initiated on north facing slopes. The remaining cases were associated with west (18%) and east (16%) facing slopes and relatively flat terrain (8%). Finally, 58% of the landslides were triggered in urban areas compared to 27% in forested areas and 8% in pastures.

4.2 Catalogs of landslides and rainfall events at local scale

At the urban center scale of Angra dos Reis, 526 landslides were linked to one of 234 rainfall events compiled. The geographic distribution of landslides is relatively heterogeneous despite a fairly large clustering (155 cases; 30%) in the colluviums of the Sapinhatuba I and Monte Castelo neighborhoods in the east-central part of the urban center (**Figure 2**). The landslides were initiated during 129 of the 234 (55%) rainfall events compiled (**Table 1**). These 129 rainfall events lasted a little more than 4 days, or 108 hours, with a minimum and maximum duration of 24 and 528 hours (22 days). The minimum and maximum number of landslides initiated by

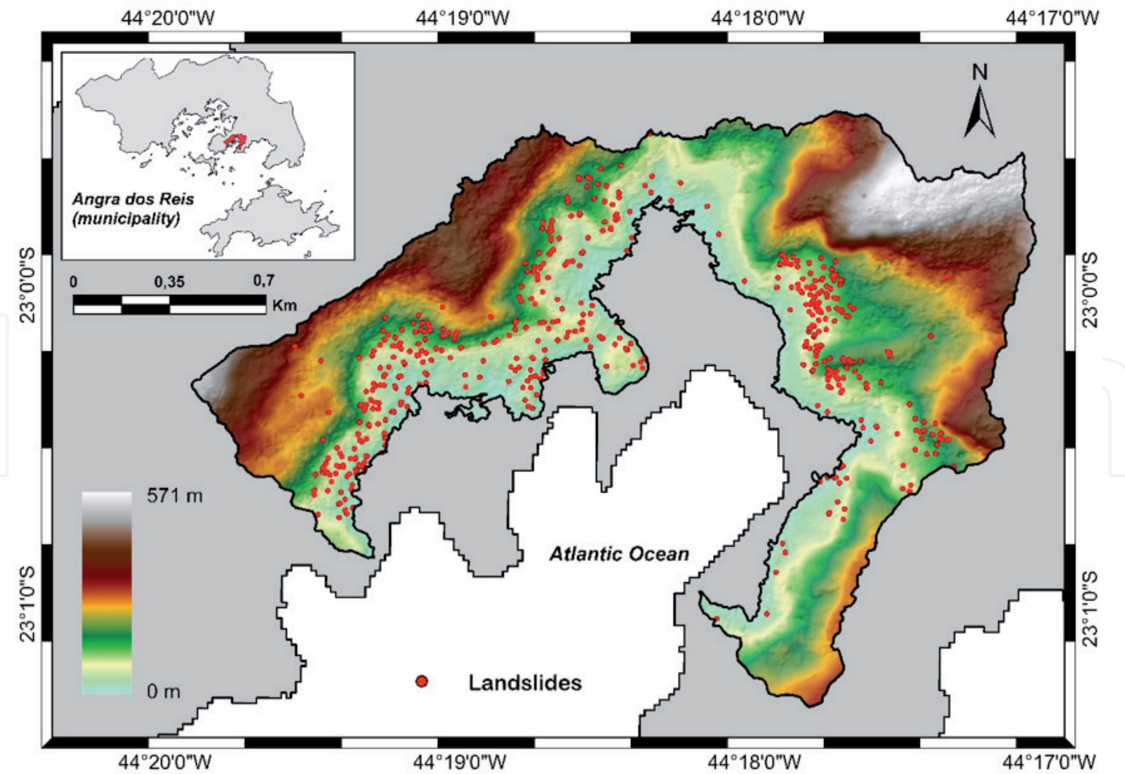

Figure 2.
Map of the urban center of Angra dos Reis. Red dots show location of the 526 landslides recorded over an area of 6.5 km².

these episodes are 1 and 38, for an average of four landslides per triggering rainfall event. More specifically, 36% (47 of 131) of the triggering rainfall events initiated a single slide, 63% (83 of 131) initiated three or fewer slides, and only 9% (12 of 131) generated ten or more ruptures.

On a seasonal basis, two-thirds of the 526 slides (66%) were initiated during the wet season. Indeed, the average number of rainfall triggering events and the ratios of triggering versus non-triggering events are 2 and 64% in the wet season (January to April), 1 and 37% in the dry season (May to August), and 2 and 59% in the transition season (September to November). On a monthly basis, January was the most significant month with an average of 25 landslides compared to only seven for all other months. 42% of the landslides occurred on gentle slopes (0 to 20°), 39% on slopes between 20 and 35 ° and 19% on steep slopes >35 °. In this respect, more landslides were recorded on steep slopes at the local scale compared to the regional scale. The slopes facing south were the most affected with 53% of the landslides, compared to 21% on slopes facing north, 13% on the east and 14% on the west facing slopes (**Figure 2**). Finally, a high proportion of landslides (76%) occurred in urban areas, while only 22% occurred in forest and pasture areas.

4.3 Definition of the rainfall thresholds for landslide events

As we mentioned in the methodological section, several ED thresholds were defined at the regional and local scales based on the overall database, but also with different subsets for the seasonality (wet and dry seasons), and the southern (JAJ) and northern (MBS) parts of the study area.

Figure 3 shows, in log–log coordinates, the distribution of rainfall conditions (D, E) that have resulted in landslides at both scales; the municipality of Angra

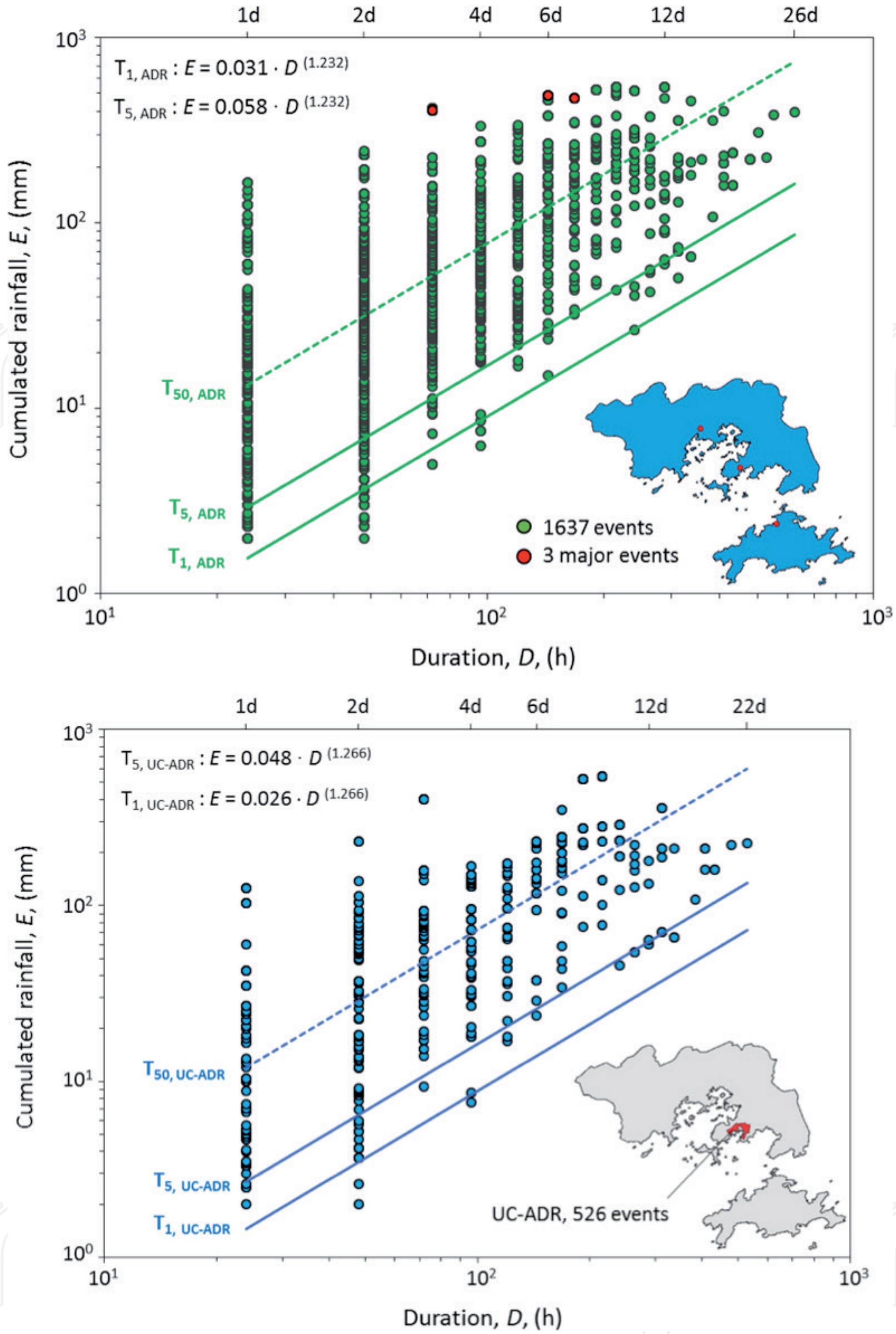

Figure 3.
Rainfall duration D (x-axis) and cumulated event rainfall E (y-axis) conditions that have resulted in landslides at the regional scale of the municipality of Angra dos Reis (upper panel) and at the local scale of the urban center (lower panel). 1% and 5% ED power law thresholds are shown with their equations (solid lines) as well as 50% (dashed line) for reference. Inset shows the study area and the localization of the three major deadly events (red dots) at the regional scale.

dos Reis (1640 landslides) and the urban center (526 landslides), with the 1% and 5% ED thresholds curves. The urban center shows a quite similar 1% ED threshold ($T_{1\ UC\text{-}ADR}$) and 5% ED threshold ($T_{5\ UC\text{-}ADR}$) to those calculated at the regional scale ($T_{1\ ADR}$ and $T_{5\ ADR}$). See **Table 1** for more details about the scale and intercept parameters.

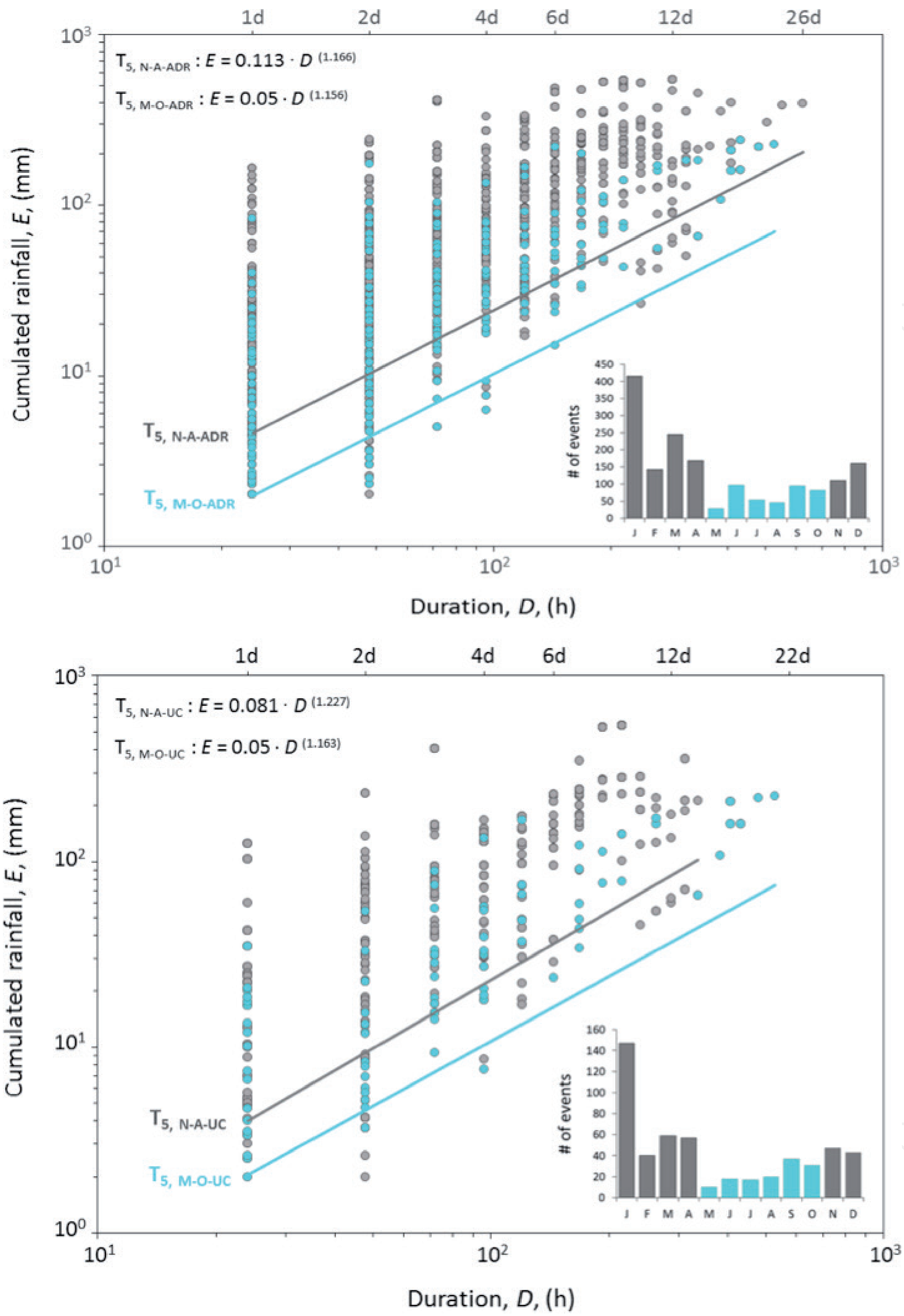

Figure 4.
Rainfall duration D (x-axis) and cumulated event rainfall E (y-axis) conditions that have resulted in landslides in the period May–October (dry season; blue dots) and for the period November–April (wet season; gray dots). Colored lines are the 5% power law thresholds and insets show the distribution of recorded landslides on a monthly basis. Upper panel shows the dataset at the regional scale and lower panel shows the dataset at the local scale of urban center.

The ED rainfall thresholds shown in **Figure 4** indicate lower 5% thresholds for the extended dry season ($T_{5\ M\text{-}O\text{-}ADR}$ and $T_{5\text{-}M\text{-}O\text{-}UC}$) by comparison to the wet season ($T_{5\text{-}N\text{-}A\text{-}ADR}$ and $T_{5\ N\text{-}A\text{-}UC}$) at both scales. Indeed, the insets clearly indicate the high monthly variability in occurrence of landslides recorded, showing obvious differences between the dry and wet season. In this case, the 5% ED thresholds were quite similar for the municipality and urban center, particularly for the dry season and with a very small difference for the wet season (**Table 1**). However, the rainfall events triggering landslides during the wet season appears of shorter duration at the local scale (24 to 336 hours) compared to the regional scale (24 to 624 hours). No difference was reported for the dry season.

Label	Area	RE	LE	Threshold	Range (h)	Uncertainty
$T_{1,\ ADR}$	R	484	1640	$E = 0.031xD^{1.232}$	24-624	$\Delta\alpha = 0.13$ $\Delta\gamma = 0{,}002$
$T_{5,\ ADR}$	R	484	1640	$E = 0.058xD^{1.232}$	24-624	$\Delta\alpha = 0.18$, $\Delta\gamma = 0.002$
$T_{1,\ UC\text{-}ADR}$	L	129	526	$E = 0.026xD^{1.266}$	24-528	$\Delta\alpha = 5.32$ $\Delta\gamma = 0.04$
$T_{5,\ UC\text{-}ADR}$	L	129	526	$E = 0.048xD^{1.266}$	24-528	$\Delta\alpha = 0.7$ $\Delta\gamma = 0.03$
$T_{5,\ N\text{-}A\text{-}ADR}$	R-Wet	1240	1240	$E = 0.113xD^{1.166}$	24-624	$\Delta\alpha = 0.19$ $\Delta\gamma = 0.02$
$T_{5,\ M\text{-}O\text{-}ADR}$	R-Dry	400	400	$E = 0.05xD^{1.256}$	24-528	$\Delta\alpha = 0.20$ $\Delta\gamma = 0.08$
$T_{5,\ N\text{-}A\text{-}UC}$	L-Wet	393	393	$E = 0.081xD^{1.227}$	24-336	$\Delta\alpha = 0.22$ $\Delta\gamma = 0.03$
$T_{5,\ M\text{-}O\text{-}UC}$	L-Dry	133	133	$E = 0.05xD^{1.163}$	24-528	$\Delta\alpha = 1.2$ $\Delta\gamma = 0.02$
$T_{5,\ JAJ\text{-}ADR}$	R-South	357	1276	$E = 0.056xD^{1.228}$	24-624	$\Delta\alpha = 0.12$ $\Delta\gamma = 0.02$
$T_{5,\ MBS\text{-}ADR}$	R-North	451	364	$E = 0.066xD^{1.252}$	24-432	$\Delta\alpha = 0.6$ $\Delta\gamma = 0.04$

Label: label of the thresholds defined in this study. Area: regional scale (R) of the municipality or local scale (L) of the urban center. RE: number of rainfall events. LE: number of landslide events. Threshold: D rainfall duration, in hours; E, cumulated event rainfall, in mm. Range: range of the validity for the threshold. Uncertainty: associated with the intercept α and the slope γ of the threshold model based on a power law.

Table 2.
Rainfall ED thresholds for the possible initiation of landslides in Angra dos Reis.

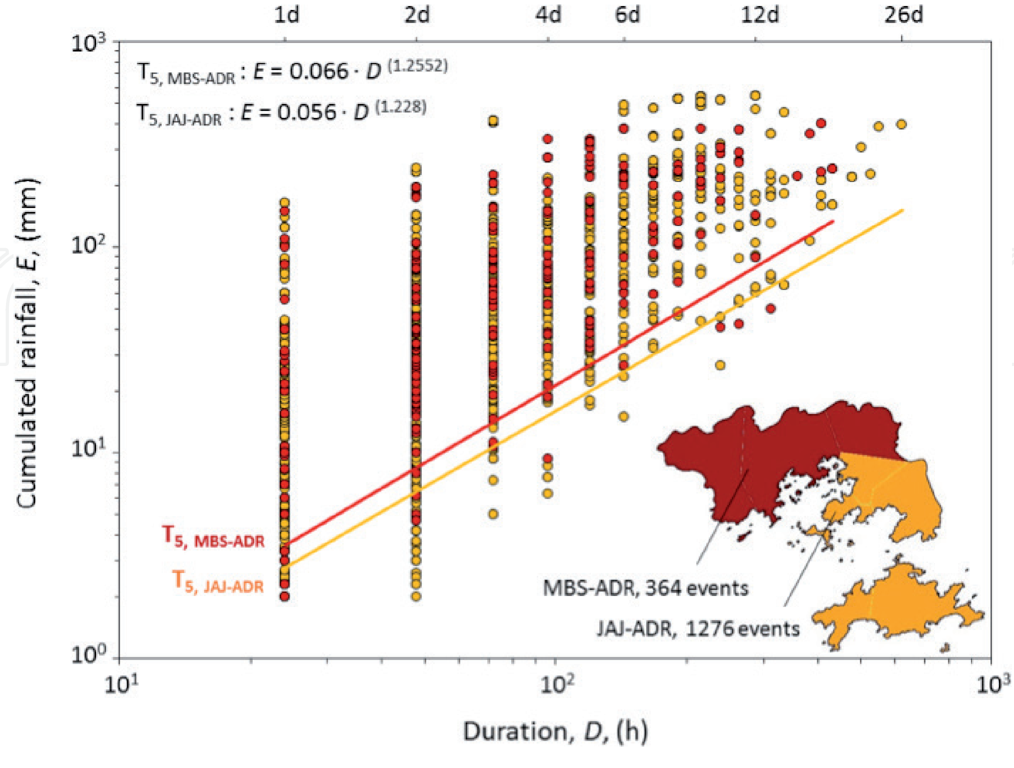

Figure 5.
Rainfall duration D (x-axis) and cumulated event rainfall E (y-axis) conditions that have resulted in landslides in the southern region (JAJ; yellow dots) and the northern region (MBS; red dots). Colored lines are the 5% power law thresholds and inset shows the geographical area covers by both regions as well as the number of landslides recorded.

Finally, the **Figure 5** shows the similar tendency of the 5% thresholds for the southern and northern regions, although the latter shows a slightly higher value. However, it is worth mentioning the significant difference between the two regions regarding the number of recorded landslides; 1276 in the southern part and 364 in the northern part of the municipality. A significant appears also in the duration of rainfall events triggering landslides, which is limited to 432 hours in the north by comparison to 624 hours in the south (**Table 2** and **Figure 5**).

5. Discussion

5.1 Landslide hazard and risk in Brazil

Several factors of a geological (volcanic activity, earthquake, lithologic faults and discontinuities, etc.), meteorological (precipitation, temperature), and human (land use) nature influence slope stability [36]. Therefore, the dynamic relationships in time and space between these different factors greatly complicate the objective assessment of landslide susceptibility and probability of occurrence for a given region and time period [37].

In the humid tropics, the majority of precipitation and its extremes are concentrated during the summer period. To this end, the warm and humid climate of southeastern Brazil favors the chemical alteration of rock and the development of saprolites, especially in hilly and mountainous environments. During major rainfall events, these are reworked by mass movements such as debris flows, superficial slides, rotational, and deep-seated landslides [38]. It is therefore not surprising that in the past several catastrophic events occurred [39–41], for example and among others in 1967 [42], 1988 and 1996 [43–45], and more recently in 2008, 2010 and 2011 [46–48]. The rapid growth of urbanization in the last decades with an improper land use [38] is certainly responsible, at least partially, for the tragic outcome of these recent disasters.

In this context, several approaches have subsequently been used to assess landslide risk: landslide susceptibility zonation using GIS-based fuzzy logic [49], electric and electromagnetic methods with geotechnical soundings [50], structural geology and kinematic analysis with stereographic projections [51, 52], analysis of morphological parameters (drainage efficiency index, slope geometry, slope angles, etc.) [53], laboratory and fields observations [54], and modeling with SHALSTAB (shallow landsliding stability model), SINMAP (stability index mapping), GEO-SLOPE (slope stability analysis), and TRIGRS (transient rainfall infiltration) software's [55–57]. Despite the limited effectiveness of these modeling procedures and the interest in mapping and vulnerability of populations to landslides, e.g. [58–60], there is still little work on the determination of rainfall thresholds favorable to landslide occurrence. Indeed, the few authors who have focused on defining rainfall thresholds in southeastern Brazil and the Serra do Mar at the regional scale, are rather thresholds based on total precipitation during major events [19, 61].

5.2 Significance of ED rainfall thresholds for hazard and risk assessment

The ED thresholds presented in this study at regional and local scales highlight the statistical dependency of the cumulated rainfall E to the rainfall duration D. In that regards, they represent appropriate rainfall thresholds for the possible occurrence of 1640 landslides in the municipality of Angra dos Reis and 526 landslides at the local scale of the urban center over a 6-year period. However, because these thresholds result of statistical modeling applied to an empirical dataset, uncertainties have been quantified using a bootstrap approach.

Figure 4 indicates a significant difference in seasonal thresholds for all duration analyzed. Surprisingly, less cumulated rainfall appear required to initiate landslides during the dry season (May–October) by comparison to the wet summer season (November–April). This result was not expected considering that usually the antecedent rainfall conditions of the wet season, and the resulting increased moisture in the soil, reduce the amount of event rainfall required to triggering landslides [30]. Unfortunately, the absence of details about the landslides recorded does not allow a better discrimination in landslide classification or typology regarding their temporal occurrence. However, the significant difference between the northern and southern regions in number of landslides triggered by rainfall events (**Figure 5**), attests for the likely influence of other environmental factors such as slope aspect, land cover type, lithological types, etc. Slope steepness does not appear to be a very important factor given the amount of landslides recorded on gentle slopes. On the other hand, even considering the size of the dataset analyzed (484 rainfall events resulting in 1640 landslides), we acknowledge that further studies are required to better understand the role of land use, land cover types, urbanization, and human induced changes that may affect the amount of rain necessary to trigger landslides locally and regionally. Finally, as mentioned by [62], the bootstrapping technique may result in optimistic estimates of the uncertainties in the thresholds determined, to which we suggest conducting similar analyses over longer time series.

In the Brazilian municipality of Angra dos Reis, heavy summer rainfall has historically triggered several landslides, causing a significant number of victims and considerable damage. The risk posed by this geomorphic hazard is particularly high due to the fact that almost 60% of the population lives in slope areas [16] and more than 25% live in areas considered to be at high risk of landslides [17]. In that regards, our data indicate that 58% of the 1640 landslides recorded occurred in urban areas, 71% on gentle slope, and 34% on south facing slopes, reflecting the exposure and risk to the population. Therefore, the interest of the municipal authorities of Angra dos Reis in establishing rainfall thresholds (i.e. **Table 2**) should allow a better anticipation of spatial and temporal occurrence of the phenomenon. The thresholds in this study could ultimately be integrated into a landslide monitoring and warning system and serve as a necessary component of hazard assessment. This is particularly pertinent considering that since the beginning of research on rain-triggered landslides in Brazil, no suitable thresholds have been proposed for the Angra dos Reis territory.

In fact, the thresholds of Guidicini and Iwasa [18] were established for the whole Serra do Mar, whose area is four times larger than that of Angra dos Reis, while the one developed by Soares [19] is not representative of the triggering conditions due to the use of an inadequate database. The thresholds proposed and to come in the near future according to the characteristics of the territory and from recent and reliable data could be an effective tool for landslide risk management.

6. Conclusion

In the mountainous and tropical environment of the municipality of Angra dos Reis in Brazil, the high frequency of intense rainfall generates several landslides that recurrently interfere with human activities and infrastructures. Lithology, land use and vegetation cover are biophysical parameters that remain to be explored in relation to the spatial and temporal dynamics of landslides, especially in a context of climate change and increasing urbanization.

The establishment of quantitative rainfall thresholds that, when reached or exceeded, are likely to trigger landslides (e.g. **Figures 3–5**) therefore appears to be a valid approach for risk management. The thresholds reported in this study could provide a relevant management tool for municipal authorities. Moreover, the establishment of thresholds based on the duration of rainfall events (ED) should be regarded as a research axis whose development is essential in risk management, particularly in order to set up a landslide monitoring and warning system. The detailed study of rainfall conditions that led to the initiation of 1640 landslides in the municipality of Angra dos Reis and 526 landslides in the urban center revealed that very small amounts of water accumulated over periods of up to 26 days are sufficient to initiate landslides (**Table 2**). These precipitations represent barely 1 to 4% of the annual average rainfall depending on the duration of the events considered. The rainfall limits appear low when compared to some of the thresholds proposed in the literature for Brazil and other tropical regions.

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