Regional rainfall thresholds for landslide occurrence using a centenary database

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Abstract. This work proposes a comprehensive method to assess rainfall thresholds for landslide initiation, using a centenary landslide database associated with a single centenary daily rainfall dataset. The method is applied to the Lisbon region and include the rainfall return period analysis that was used to identify the critical rainfall combination (cumulated rainfall-duration) related to each landslide event. The spatial representativeness of the reference rain gauge is evaluated and the rainfall thresholds is assessed and calibrated using the receiver operating characteristic (ROC) metrics.

Results show that landslide events located up to 10 km from the rain gauge can be used to calculate the rainfall thresholds in the study area; however, such thresholds may be used with acceptable confidence up to 50 km distance from the rain gauge. The obtained rainfall thresholds using linear and potential regression have a good performance in ROC metrics. However, the intermediate thresholds based on the probability of landslide events, established in the zone between the lower limit threshold and the upper limit threshold are much more informative as they indicate the probability of landslide event occurrence given rainfall exceeding the threshold. This information can be easily included in landslide early warning systems, especially when combined with the probability of rainfall above each threshold.

1 Introduction

Rainfall is the most important physical process for the landslide triggering in Portugal (Zêzere et al., 2015; Vaz and Zêzere, 2016) as worldwide (e.g. Crozier, 1986; Crosta and Frattini, 2008). However, the relation between rainfall and landslides is indirect and typically include a process cascade where the rainfall is followed by the infiltration into the soil, which increases the pore-water pressure that is responsible at last by the decrease of the slope materials shear strength (Terlien, 1998; Glade and Crozier, 2005).

During the last decades, the relationship between landslides and rainfall has been tentatively established by the assessment of rainfall thresholds, i.e., rainfall conditions (cumulated rainfall, intensity) that when reached or exceeded can induce a landslide event (Reichenbach et al., 1998; Guzzetti et al., 2007). The rainfall thresholds for slope failure have been proposed following the physical and the empirical approach. The first approach considers the physical basis of the process, using hydrological models and stability calculations (Terlien, 1998; Iverson, 2000; Frattini et al., 2009). However, it demands high

resolution data (e.g. groundwater conditions; shear strength properties) that often are not available for large areas (Guzzetti et al., 2007). The second approach is statistically-based and is sustained by historical records regarding landslide events and rainfall data series (Guzzetti et al., 2007). Several thresholds have been proposed worldwide using the empirical approach that can differ according to the kind of rainfall measurements and variables and the number of rain gauges used to calculate the threshold, as well as the geographical extend where the threshold is applied.

The most common empirical rainfall thresholds used at the local and regional scale are the rainfall intensity and duration (I-D) threshold, the event-duration (E-D) threshold, the antecedent rainfall threshold, and the combined threshold. The I-D threshold link the total height of rainfall and the instantaneous rainfall intensity (Caine 1980) and has been widely used as a power-law threshold (e.g. Guzzetti et al., 2008; Saito et al., 2010; Brunetti et al., 2010). It has been applied with good performance especially for shallow landslides, triggered by short and intense rainfall. Alternatively to the former, the E-D threshold associates the rainfall cumulative event and the rainfall event duration (e.g. Peruccacci et al., 2012). The antecedent rainfall thresholds assess the influence of the antecedent rainfall on the groundwater levels and soil moisture, thus acting as landslide preparatory factor. This is particularly important for deep-seated landslides induced normally by long-lasting rainfall periods (Martelloni et al., 2012). However, the definition of the critical rainfall period for the antecedent rainfall is an important source of bias (e.g. Guzzetti et al., 2007; Zêzere et al., 2015) and different periods have been proposed in the literature ranging from few days to several months (e.g. Glade et al., 2000; Cardinali et al., 2006). Finally, the combined thresholds include several combination as the rainfall event combined with rainfall intensity (e.g. Onodera et al., 1974); the event rainfall with the antecedent rainfall (e.g. Pereira and Zêzere, 2012); the event rainfall with the antecedent calibrated rainfall (e.g. Zêzere et al., 2005).

The rainfall thresholds for landslide activity obtained in a study area cannot be extrapolated for other regions, namely because of changes regarding the climatic regime (Glade et al., 2000). To allow the comparison of rainfall thresholds obtained in different areas, the normalization of rainfall data has been made using two climatic indices: the mean annual precipitation (MAP) (Cannon, 1988) and the rainy day normal (RDN) (Wilson, 1997). The different rainfall parameters can be divided by the two climatic indices to obtain, for instance, the normalized intensity-duration (e.g. Wieczorek et al., 2000), the normalized event-duration (e.g. Giannecchini, 2005) and the normalized antecedent rainfall (e.g. Aleotti, 2004).

The rainfall measurements used to assess rainfall thresholds for landslide activity can be based on a single reference rain gauge (e.g. Zêzere et al., 2005; Marques et al., 2008; Martelloni et al., 2012) or on multiple rain gauges (e.g. Peruccacci et al., 2012). The near distance, similar elevation and topographical and morphological settings are pointed as the preferable criteria to select the representative area of a rain gauge (Brunetti et al., 2010). However, the distance to where the rain gauge is spatially representative is a critical point that often is not addressed, which can be an additional source of bias for the threshold definition, as pointed out by Nikolopoulos et al. (2015).

The assessment of rainfall thresholds implies the consideration of two types of information, linking rainfall and landslides in a single study area: the rainfall events that triggered landslides in a defined time period in the past; and the rainfall events that did not trigger landslides in the same time period. Considering the rainfall data sets associated (and non-associated) with

landslide events two distinct rainfall thresholds can be defined: (i) the lower limit threshold, which is the limit below which the landslides have not been recorded; and (ii) the upper limit threshold, which is the limit above which landslides have always been recorded (Glade et al., 2000). The zone between the lower limit and upper limit thresholds includes rainfall conditions that triggered and did not trigger slope failures in the past. As a rule, the uncertainty increases with the increasing gap between the lower limit and upper limit thresholds. Therefore, between the lower threshold and the upper threshold different probabilities of landslide occurrence exist that are important to quantify.

The main purpose of this study is to present and discuss a comprehensive method to assess rainfall triggering thresholds, using a centenary landslide database associated with a single centenary daily rainfall dataset. In addition, five specific objectives are stated: i) to identify the critical combinations of cumulated rainfall-duration for landslide occurrence; ii) to compute the antecedent rainfall thresholds using linear and potential regression and defining the lower limit and the upper limit rainfall thresholds; iii) to assess the thresholds performance using receiver operating characteristic (ROC) metrics; iv) to estimate the probability of rainfall threshold and the probability of landslide events above a specific rainfall threshold; and v) to identify the geographical area where the rainfall thresholds can be applied.

2 Study area and general characteristics of the rainfall regime

The Lisbon region is located in the southern Portuguese Estremadura, being divided in two parts by the Tagus River (Fig. 1). The landscape is marked by hills and valleys and three mountains of limited extension and altitude (Fig. 1): the Montejunto Mountain at the Northwest (666 m altitude), the Sintra Mountain at the West (528 m) and the Arrábida Mountain at the South (501 m).

The climate in the Lisbon Region, as in Portugal, is influenced by the subtropical anticyclone and the sub-polar depression zone (Espírito Santo et al., 2014; Lima et al., 2015). The atmospheric general circulation combined with the orography and the oceanic and continental influences are the most important factors that shape the regional climate (Nunes and Lourenço, 2015). The rainfall regime is typically irregular, with an inter-annual and intra-annual variability (Kutiel and Trigo, 2014). The inter-annual variability is notorious in the centenary annual rainfall data registered at the Lisboa-Geofísico rain gauge (Fig. 2). The mean annual rainfall (MAR) is 709 mm, but the variability is very high and wet years can be followed by severe dry years. In some climatological years the annual rainfall reached the double of MAR (e.g. more than 1400 mm in 1876/77), while other climatological years did not reach half of the MAR (e.g. less than 300 mm in 2004/05).

The intra-annual rainfall regime is characterized by the seasonality (Fig. 3), with two important seasons (dry and wet) separated by transition periods (Ribeiro et al., 1999). During two months of summer (July and August) the rainfall is almost absent in quantity and frequency. On average, these months concentrate only 1.3 % of the annual rainfall. The Azores anticyclone influence, in its north-westerly position, explains the warm and dry air that affect the Lisbon region during this season (Trigo and DaCamara, 2000). The monthly rainfall is highest from October to March, however with a strong inter-annual variability. On average, this period concentrates more than 75 % of the annual rainfall, with a frequent peak in

November. This wet period is explained by the large-scale circulation led by the Icelandic low pressure system, which bring moist air responsible for rainfall events (Trigo and DaCamara, 2000). September, April, May and June are transition months and can be highly variable from one year to other year concerning the amount of rain.

As a rule, the circulation weather types, associated with high rainfall amounts, are of cyclonic and westerly type (Trigo and DaCamara, 2000; Ramos et al., 2014). Recently, it was found that the winter storms in Europe, responsible for large accumulations of precipitation, have a tendency for temporal cluster (Mailier et al., 2006; Vitolo et al., 2009; Pinto et al., 2013). Therefore, storms with high magnitude are followed by other storms, increasing the probability to induce other natural hazards, as floods and landslides.

3 Data and methods

3.1 Identification of landslide events

The landslide database used in this study includes the DISASTER database and has detailed information about the date and location of landslides occurrence. The DISASTER database was carried out exploring several daily and weekly newspapers, published in Portugal between 1865 and 2010, and includes all the landslides that caused fatalities, injuries, missing people, evacuated and homeless people. The method used to construct the DISASTER database has been widely described and can be found in Zêzere et al. (2014). Additionally, using the same newspaper sources, landslides that did not caused any human damage during the same time period were identified and included in the database that supported this study. It should be pointed out, that fall of walls and instabilities directly resulting from engineering works were rejected. Similarly, the landslides in active coastal cliffs were not included in the database. The database structure is divided in two sections: landslide features and landslide damages. The first section includes information of landslide type; temporal and spatial location; triggering factor; and newspaper metadata. The second section refers to human consequences of landslides (fatalities, injuries, missing people, evacuated and homeless people), and direct and indirect damage in buildings, structures, roads and railroad.

Our analysis is focused on the date of landslide occurrences. So, the newspapers are a reliable data source, despite the existing uncertainty concerning the spatial location of many reported landslide events, as well as on their type. Only landslides with at least 1 day of accuracy were included in the database. The spatial accuracy of landslides cases was classified, following Zêzere et al. (2014), in 5 classes: (i) location with exact coordinates (accuracy associated with scale 1:1 000); (ii) location based on local toponymy (accuracy associated with scale 1:10 000); (iii) location based on local geomorphology (accuracy associated with scale 1: 25 000 scale); (iv) location in the centroid of the parish; and (v) location in the centroid of the council. A total of 400 landslide cases were inventoried being the majority (83 %) located with accuracy corresponding to classes (i) to (iii). These landslides affected clay (40.24 %), sandstone and conglomerate (22.52 %), limestone (16.52 %), volcanic (11.11 %), marly and marly limestone (9.01 %) and granite (0.60 %). The landslide type

was classified following the Cruden and Varnes (1996) classification scheme. The slides are the dominant landslide type in the database (53.8 %), followed by falls (14.4 %). Flows and complex slope movements are less representative (2.4 % and 1.5 %, respectively). The landslide type is unknown in 27.9 % of cases. In this study the analysis was performed for all landslide types, following the approach of similar studies (e.g. Brunetti et al., 2010; Rosi et al., 2012; Peruccacci et al., 2017).

3.2 Selection of rain gauge and identification of critical rainfall combinations

In this study the following definition was adopted for landslide event: an individual landslide or a set of landslides that occurred on a precise date (day). In those cases where the activity period of a landslide was reported as lasting during several days, the first day of the period was considered for the landslide event.

The selection of the reference rain gauge took into account the available time series, the data quality and resolution and the climatic representativeness. The daily rainfall data was collected at the Lisboa-Geofísico rain gauge (Latitude 38.72 °N, Longitude 9.15 °W, Elevation 77 m), located within the Lisbon city. The rainfall daily measurements at Lisboa-Geofísico started in 1864, being one of the few rain gauges with centennial-long daily records in Portugal. A long time series of rainfall data is an important condition to create comprehensive thresholds that are based on the analysis of the rainfall return period. In addition, this rain gauge presents a reliable data, whose quality and completeness was already tested and confirmed by Kutiel and Trigo (2014). The rainfall measurements have been made without interruption and always in the same place, since 1864. Furthermore, the rain gauge is climatically representative of the Lisbon region, with a rainfall regime influenced mainly by the atmospheric general circulation and the oceanic proximity.

The daily rainfall refers to the period between 9:00 UTC of the previous day and the 9:00UTC of the day of measurement, whereas the landslides dates are ascribed to a period between the 0:00UTC to 23:59UTC. Due to this difference, the date of each landslide event reported by the newspaper was compared with the daily rainfall registered in three days (starting from the day before up to the day after), and the day registering the highest rainfall amount was selected as the day of the landslide event.

The reconstruction of accumulated rainfall follows the method proposed by Zêzere et al. (2005). In a first step, the daily rainfall data registered at the Lisboa-Geofísico rain gauge during the period 1864/65 - 2009/10 were organized by climatological year (September to August). The decision to use the climatological year, instead of the hydrological year (October-September), is justified by the rainfall regime of the study area. Starting the analysis in September, after the month with the low values of rainfall (August), we capture the complete transition period towards the wet season in each year. Afterwards, for each day, from 1864 to 2010 the cumulative antecedent rainfall was calculated for the durations of 1, 2, 3, 4, 5, 10, 15, 20, 30, 40, 50, 60, 75 and 90 days.

The maximum annual records of daily rainfall and accumulated rainfall for each duration were extracted and analysed using the theoretical distribution described by Gumbel (Gumbel, 1958). This distribution is also known as the distribution of Ficher-Tippett and is applied for the extreme values. With the Gumbel law it is possible to obtain the probability of occurrence of each rainfall value within the series with *N* values. The reduced Gumbel distribution (*y*) is calculated with the following Eq. (1):

$$y = -\ln(-\ln\frac{m}{N+1}) , \quad (1)$$

Where, *m* is the position number of the respective observations and *N* is the total number of observations. Considering this distribution, the theoretical frequencies can be calculated by the average and standard deviation for the reduced Gumbel distribution (*My* and *Sy*) and for the rainfall values (*Mx* and *Sx*). The following Eq. (2) expresses the theoretical trend:

$$y = \alpha(x - \mu), \quad (2)$$

Where, *y* is the reduced variable and *x* the rainfall value. The parameters α and μ are calculated as follows:

$$1/\alpha = Sx/Sy, \quad (3)$$

$$\mu = Mx - My/\alpha, \quad (4)$$

Finally, the probability of exceedance of any rainfall value is given by the Eq. (5):

$$P(x) = 1 - e^{-e^{-y}}, \quad (5)$$

For each landslide event the cumulative antecedent rainfall was assessed for the durations of 1, 2, 3, 4, 5, 10, 15, 20, 30, 40, 50, 60, 75 and 90 days. For each antecedent rainfall the return period (RP) was calculated with the following Eq. (6):

$$RP = \frac{1}{1-e^{-e^{-y}}}, \quad (6)$$

The pair (cumulated rainfall-duration) with the highest return period was considered as the critical rainfall combination responsible for triggering the landslide event. This assumption is not physically based, but has been applied in previous work (e.g. Marques et al., 2008; Zezere et al., 2008; Zêzere et al., 2015) and provides the best discrimination of the rainfall events related with landslide activity (Zêzere et al., 2005). Moreover, this approach agglomerates the rainfall that triggered the landslide event and the antecedent rainfall that contributed as landslide preparatory factor.

As it was previously mentioned, our landslide database was collected from newspaper sources and in some cases the rainfall triggering is not clear. Therefore for threshold calculation we decided to use only the landslide events whose critical rainfall combination have a return period exceeding 3 years. The boundary is arbitrary, but this criterion reduces the possibility of considering landslide events whose triggering factor was other than rainfall (e.g. human action). The landslide events associated with critical rainfall combinations with return period less than 3 years were assumed as not triggered by rainfall.

Finally, the climatological years without landslide records in the database were selected and the maximum yearly cumulated rainfall was identified for durations lasting from 1 to 90 consecutive days. These data were further used as rainfall events that did not generated landslide events and are crucial for the thresholds definition and calibration.

3.3 Critical distance from the rain gauge

The critical distance where the rain gauge is regionally representative was evaluated by drawing several buffers up to 60 km from the rain gauge (5, 10, 15, 20, 30, 40, 50 and 60 km). The ratio between the non-rainfall triggered landslide events and the rainfall triggered landslide events within each buffer was used to identify the area where the rain gauge is representative.

During the analysed time period (1864/65 - 2009/10) landslides in the study area were mostly triggered by rainfall and the earthquake triggering can be neglected (Vaz and Zêzere, 2016). The human action was an additional landslide triggering factor, in particular through artificial cuts and drainage constrains associated with the progressive enlargement of urban areas. As it was already mentioned, the reference rain gauge is located in the city of Lisbon, where the landslides induced by human action are expected to be in higher number when compared with the outside of the urban area. Following this assumption, the ratio between the non-rainfall triggered landslide events and the rainfall triggered landslide events should decreases as the distance from the gauge increases. If this relation does not occur we assume that the rain gauge is not anymore representative for the corresponding buffer. Therefore, the lowest ratio between non-rainfall triggered landslide events and rainfall triggered landslide events was considered to define the critical distance where the rain gauge is regionally representative to assess rainfall thresholds for landslide occurrence.

3.4 Rainfall triggering thresholds assessment and calibration

Landslide events registered within the critical distance from the rain gauge were considered and rainfall thresholds were established using linear and potential regression, based on cumulated rainfall-duration with the highest return period. The lower limit and the upper limit rainfall thresholds were also defined following the suggestion by Glade et al. (2000). The lower limit and the upper limit rainfall thresholds were defined by linear regression both based on two pairs. The lower limit was established by selecting iteratively two landslide events associated to different durations with the lowest values of cumulated critical rainfall and ensuring that the complete set of landslide events fall above the threshold. The upper limit was established by selecting iteratively two highest pairs (cumulated rainfall/duration) that did not triggered landslides and ensuring that the complete set of non-landslide events fall below the threshold.

When representing thresholds we avoid using logarithm scales and thresholds were established as linear relationship instead of power law, with a single exception (the potential regression threshold). These options maximize the zone between the lower limit and upper limit thresholds, thus allowing the distinction between rainfall events that generated (not generated) landslide events.

The performance of rainfall thresholds was evaluated using ROC metrics. ROC analysis are commonly used to validate susceptibility landslide models (Beguería, 2006; Kappes et al., 2011) and it is based on confusion matrices. The principles

used in theses analyses can also be applied to calibrate the rainfall thresholds (e.g. Staley et al., 2013, Gariano et al., 2015a, Zêzere et al., 2015). The confusion matrix is used to assess the correct and incorrect predicted observations, for positive and negative cases (Beguería, 2006). Therefore, the analysis is based on the evaluation of True Positive (TP), False Negative (FN), True Negative (TN) and False Positive (FP) cases. When, applied to rainfall thresholds the TP correspond to the landslide events which rainfall combination (cumulated rainfall-duration) is above the threshold. The FN are landslides events for which the rainfall combination (cumulated rainfall-duration) is below the threshold. The rainfall combinations that did not resulted in landslides events are classified as TN if they are below the threshold or FP if they are above the threshold.

Also, four ROC metrics functions described by Staley et al. (2013) were used in this study (Table 1). The True Positive rate (TP_r) is the proportion of landslide events that were correctly predicted by the threshold (Table 1). The False Positive rate (FP_r) is the proportion of rainfall events above the threshold for which there is no information of landslide occurrence. The False Alarm rate (FA_r) is the ratio between false predictions and the complete set of rainfall events above the threshold. The Threat Score (*TS*) is used to evaluate the threshold to maximize the number of correct predictions while minimize the rate of FP and FN. A *TS* = 1 represents a perfect model, being reduced by the incorrect predictions.

The probability of a rainfall event above the rainfall threshold resulting in a landslide event, was measured by the Positive Predictive rate (PP_r), which was previously described by Bradley (1997) and Fawcett (2006). The PP_r measures the relation between the rainfall events above the threshold that resulted in landslide events and the complete set of rainfall events located above the threshold, as follows:

$$PP_r = \frac{TP}{TP+FP} \ , \quad (7)$$

Therefore, the PP_r is the opposite of the FA_r, and can also be calculated by the expression:

$$PP_r = (1 - FA_r) \ , \quad (8)$$

Using this approach, several linear rainfall thresholds were plot in the zone between the lower limit and the upper limit rainfall thresholds, and the corresponding PP_r were calculated in order to compute the probability of landslide event associated to each threshold. In addition, the probability of each rainfall threshold was computed based on the return period of the corresponding cumulated rainfall-duration.

Lastly, the performance of the lower limit threshold was assessed beyond the critical distance of the rain gauge. For each buffer referred in Sect. 3.2 the ratio between the FN and the total set of landslide events (TP + FN) was systematically evaluated. We assume the lower limit threshold can only be applied to those buffer distances where this ratio remains stable.

4 Results

4.1 Landslide events and critical distance from the rain gauge

Within the area located up to 60 km-distance from the reference rain gauge 223 landslide events were identified dating from 1865 to 2010 (Fig. 4). The return period computed for the cumulated rainfall registered from 1 to 90 consecutive days prior 92 landslide events does not exceed 3 years. Therefore, according to the criterion defined in Sect. 3.2, these landslide events were assumed not to have been triggered by rainfall.

The ratio between the number of non-rainfall triggered landslide events and the number of rainfall triggered landslide events was calculated for each buffer zone showed in Fig. 4. The results are summarized in Table 2 and were used to define the critical distance where the rain gauge is regionally representative, and to select the landslide events considered to compute the rainfall thresholds. We acknowledge the ratio differences occurred only in the second decimal place (Table 2), but these differences can be interpreted considering the characteristics of the study area. Within the 5 km buffer the calculated ratio is relatively high (0.65). The first buffer zone includes the Lisbon city centre, which explains the high number of landslides triggered by factors other than rainfall, mainly due to human actions. In the following buffer zone (10 km) the ratio decreases to 0.63. This decrease was expected as the urban area extension decreases in the second buffer, thus justifying the lower number of non-rainfall triggered landslides. The ratio between the non-rainfall triggered and the rainfall triggered landslide events increases to 0.66 within the 15 km buffer zone, and the ratio ranges between 0.66 and 0.70 in the next buffer zones up to 60 km distance from the rain gauge. The increasing ratio in distances exceeding 10 km from the rain gauge cannot be attributed to the occurrence of a non-expected high number of non-rainfall triggered landslide events, but can only be explained by the decrease of spatial representativeness of the rain gauge data in areas beyond the 10 km distance. Therefore, we consider the 10 km distance the critical distance where the rain gauge is representative, and the rainfall thresholds were computed considering only the landslide events registered within this zone.

In the area located up to 10 km distance from the reference rain gauge of Lisboa-Geofísico 60 landslides events, with return period below 3 years, were assumed as non-rainfall triggered landslides, and therefore were not considered for the threshold calculation and analysis. Moreover, 96 landslide rainfall-triggered events were identified, which include 187 individual landslides. The yearly and monthly distribution of these landslide events are shown in Fig. 2 and Fig. 3, respectively. The rainfall-triggered landslide events occurred mainly in wet years: 89 % of total landslide events were registered in years with rainfall above the mean annual rainfall (MAR). The climatological years 1876/77, 1946/47 and 1968/69 are in the top regarding the number of landslide events (6 events in each year). In these three climatological years the annual rainfall was above 933 mm at the reference rain gauge, which exceeds the MAR more than 30 %. However, there is not a direct relationship between the MAR and landslide events because landslide occurrence is usually related with rainfall events occurred in a few days or weeks, which are not expressed by the mean annual rainfall. Indeed, landslide events were also registered in ten years with annual rainfall below MAR, as was the case of 1909/10 that registered two landslide events.

The monthly distribution of landslides events follows the rainfall distribution along the year in a Mediterranean climate, with dry summers and wet winters. The landslide events are essentially coincident with most rainy months, as 92 % of events occurred from November to March. Within this period, January and February stand out with the highest concentration of landslide events (24 % and 22.9 %, respectively). Besides the monthly rainfall percentile, Fig. 3 represents the 30-day cumulative antecedent rainfall for each landslide event and points out that 96 % of landslide events are above the 70th percentile. If we consider the 90th percentile this value decrease to 79 %, but it continues to highlight the exceptionality of rainfall during the 30 days before the triggering of landslides.

For each landslide event the critical cumulated rainfall-duration was obtained following the method described in Sect. 3.2. The obtained critical durations associated with landslide events range from 1 to 90 consecutive days. The monthly distribution of critical durations is showed in Fig. 5 for the rainfall-triggered landslide events. The shorter durations rainfall events (less than 20 consecutive days) occurred mainly from September to December (56 %), in the beginning of the rainy period. On contrary, when associated with longer durations rainfall periods (more than 20 consecutive days) the landslides events were more frequent from January to May (86 %).

Figure 6 illustrates the cumulated rainfall-duration combinations that resulted in landslide events and the typical return periods established for 3, 5, 10, 25, 50, 100, 150 and 200 years. Around 64 % of the cumulated rainfall-duration that resulted in landslide events have a return period below 10 years. However, four landslide events had a rainfall amount and duration with a return period very high, above 150 years. Fig. 6 also identifies the landslide events that include multiple landslides and the landslide events that are constituted by a single landslide. The distribution of both groups is inconclusive, as the landslide events containing multiple landslides are not always directly related with the exceptionality of the rainfall event, i.e., with critical cumulated rainfall-duration combination with higher return period.

4.2 Rainfall thresholds for landslide triggering

The rainfall conditions (cumulated rainfall-duration) associated with each landslide event were considered to define rainfall thresholds using linear and potential regression (Fig. 7). The linear regression follows the equation $R = 5.5\ D + 124.6$, where D is the duration in days, whereas the potential regression follows the equation: $R = 67.8\ D^{0.46}$ (Table 3). The coefficient of determination is very high in both cases (R^2 = 0.8 and 0.9, respectively). Both rules can be used as rainfall threshold for landslide occurrence in the study area; however none of them ensure a low number of False Negative occurrences (i.e. landslide events below the threshold).

To calibrate the thresholds, the maximum yearly rainfall for each duration (1 to 90 consecutive days) was calculated for those climatological years without records of landslide events in the analysed period (1864/65 - 2009/10). These records represent rainfall events not associated with landslides and are symbolized by grey dots in Fig. 7 (1428 dots). The majority of these rainfall events (96.6 %) drop below the threshold obtained with the potential regression. However, there are 57 false negatives occurrences (i.e. events that occurred without being predicted), as well as 48 false positives (i.e. rainfall events lying above the threshold, without any landslide reported).

In the next step, the lower limit and the upper limit rainfall thresholds were determined. The former establish the threshold below which there are no true positives (landslide events), whereas the latter establish the threshold above which there are no false positives (rainfall events without landslides). The lower limit threshold follows the equation $R = 4.4D + 56.5$, and the upper limit threshold follows the equation: $R = 7.3D + 235.8$, where D is the duration in days (Table 3).

Table 3 also summarizes the ROC metrics for the regression thresholds (linear and potential) and the lower limit and the upper limit thresholds. The TP_r measure the proportion of landslides events that occurred when the combinations of rainfall-duration are exceeded and shows the efficiency of a threshold to predict a landslide event. On the other hand, the FP_r measures the proportion of combinations of rainfall-duration that are above the threshold but did not result in any known landslide event. For the potential regression threshold, the TP_r is not very high (0.41, best value is 1) but the FP_r is a good result (0.03, the best value is 0) which means that the threshold have a low probability of a false detection. The TP_r is equal to 1 for the lower limit threshold, considering that it was drawn to avoid FN occurrences. However, the FP_r and the FA_r are very high (0.37 and 0.85, respectively) as consequence of the typical low values of the threshold. The lower limit is a conservative threshold, whose main advantage is predicting all the landslide events, but also including a very high number of False Positive events. On the contrary, the upper limit thresholds is only surpassed by True Positives occurrences, so the FP_r and FA_r have the best result (0 value); however, the TP_r is very low (0.03) reflecting the high number of False Negative events. The Threat Score (TS*)* provides a better understating of each threshold performance as it relates the TP, FN and FP occurrences. The linear regression threshold has the best result with 0.29 of TS, when compared with the potential regression threshold (0.27), the lower limit (0.15) and the upper limit (0.03) thresholds (Table 3). The False Alarm rate (FA_r) also gives a better result for the linear regression threshold in comparison with the potential regression threshold (0.47 and 0.55, respectively).

Although only the FP_r returns very good values, the regression thresholds, linear or potential, can be used as acceptable thresholds to predict landslide events in the study area. However, the lower limit and the upper limit thresholds should not be excluded, as the zone between these rainfall thresholds defines the boundary conditions where any rainfall event may (or may not) originate a landslide event.

4.3 Probability of landslide event and probability of rainfall above the threshold

The PP_r summarized in Table 3 gives the probability of a rainfall event resulting in a landslide event when the threshold is exceeded. The value ranges from 0 to 1 where 1 indicates 100 % probability of landslide occurrence. Accordingly, when the lower limit threshold is exceeded, the probability of occurrence of a landslide event is relatively low (0.15). On contrary, when the upper limit threshold is reached the occurrence of a landslide event is certain ($PP_r = 1$). The PP_r associated with the regression thresholds is close to 0.5, being higher for the linear trend in comparison with the potential trend (0.53 and 0.45, respectively).

The systematic comparison between True Positives and False Positives and the PP_r calculation were taken into consideration to draw five intermediate rainfall thresholds in the zone between the lower limit and the upper limit rainfall thresholds,

representing the 20 %, 30 %, 40 %, 50 % and 60 % probability of occurrence of landslide events (Table 3 and Fig. 8). Within this chart, any rainfall event exceeding the PP_r *x* % threshold has the *x* % probability to generate a landslide event in the study area. Further probabilities were not possible to compute due to lack of data.

To analyse the performance of the PP_r rainfall thresholds presented in Fig. 8, the ROC metrics were calculated and are summarized in Table 3. As expected, the False Alarm rate decreases as the PP_r increases, and the same occurs with the True Positive rate and the False Positive rate. According to the Threat Score (TS), the PP_r 40 % and the PP_r 50 % are the rainfall thresholds with the best performance (TS = 0.34 in both cases).

The return period of the rainfall associated to each calculated threshold presents a wide variation according to the considered number of consecutive days of cumulated rainfall (Fig. 9). As a rule, shorter durations (below 10 days) present a high return period in comparison with longer durations, independently on the type of rainfall threshold. In the cases of the upper limit threshold, the PP_r 60 % and the PP_r 50 % thresholds, the obtained return periods for the shorter durations are less realistic and the corresponding rainfall values were never registered in the rainfall data series of the Lisboa-Geofísico rain gauge.

Figure 9 also shows that rainfall threshold is easier to reach for periods ranging from 15 to 45 consecutive days, namely for the regression threshold (linear), the lower limit threshold, and the PP_r 20 %, PP_r 30 % and PP_r 40 % thresholds. For the mentioned durations these thresholds will be exceeded by rainfall events with return period less than 10 years. However, for durations longer than 45 consecutive days, the return period of the corresponding rainfall denotes an increase trend for all the thresholds, although the return period remains lower, when compared with periods less than 10 consecutive days.

Data summarized in Fig. 8 and 9 can be combined to better characterize any rainfall threshold. Taken as example the PP_r 60 % threshold, we can state that the highest yearly probability for this threshold to be exceeded is 5 % (20 year-return period) associated to 30 to 60 consecutive days. The probability of landslide occurrence is 60 % given rainfall exceeding the threshold. Therefore, the maximum yearly combined probability of a landslide event associated with the PP_r 60 % threshold is 3 %.

4.4 Regional performance of the lower limit threshold

Although the rainfall thresholds for landslide occurrence were defined taking in consideration the landslide events registered up to 10 km distance from the reference rain gauge of Lisboa-Geofísico, we admit that the obtained thresholds may be valid for distances larger than 10 km. In accordance, the performance of the lower limit threshold was evaluated for each buffer zone represented in Fig. 4. The ratio between the FN and the total set of landslide events (TP + FN) for the different buffer zones is summarized in Table 4. As expected, the lowest ratio (0.167) corresponds to the buffer zone of 10-15 km. The ratio remains relatively stable within buffer zones up to 50 km distance from the rain gauge (ratio ranging from 0.2 to 0.297), and increases significantly in the buffer zone of 50-60 km (0.5). Therefore, taking into account the ratio FN/(TP+FN) we can conclude that the prediction model remains efficient up to 50 km distance from the rain gauge. Consequently, although

established with landslide data registered up to 10 km distance, the thresholds identified for the Lisboa-Geofísico rain gauge may be applied with reasonable confidence for the area within 50 km distance.

5 Discussion

This work describes a comprehensive method to establish rainfall thresholds based on a reference rain gauge located in an urban area. Along the work a few methodological issues were highlighted, which are discussed in the following sub-sections.

5.1 The concept of landslide event

The concept of landslide event is not straightforward as it has been applied in literature to describe both a landslide or a set of landslides usually related with a specific triggering factor, such as an intense rainstorm (Crozier and Glade, 1999; Zêzere et al., 2014). When the landslide event is a single landslide, generally there is no problem to identify the date of the event that will be related with daily rainfall data for the rainfall threshold assessment. However, when several landslides are triggered over consecutive days in a study area, this may be a source of bias for the rainfall threshold definition. Usually, a date between the start and the end of the rainfall event is selected (e.g. Gullà et al., 2012; Gariano et al., 2015b), and therefore, a unique combination of cumulated rainfall-duration is calculated. The selection of the landslide event date is critical for this method as it can lead to the overestimation of the threshold, particularly if the end date of a long-lasting rainfall event is chosen. In these cases, the chosen cumulated rainfall-duration may be not representative of the triggering conditions of landslides that occurred in the beginning of the event. To address this problem, in this work a landslide event was considered as an individual landslide or a set of landslides that occurred on a precise date (day). Therefore, in those cases where different landslides occurred in consecutive days, each day was considered as a landslide event and the corresponding antecedent rainfall was used for the rainfall threshold assessment. In addition when the activity period of a landslide was reported as lasting during several days, the first day of the period was considered for the landslide event.

5.2 The use of one or several rain gauges to assess rainfall thresholds

Several benefits and drawbacks can be outlined regarding the use of a single rain gauge or multiple rain gauges to assess rainfall thresholds for landslide initiation. The use of multiple rain gauges is a typical option to assess rainfall thresholds (e.g. Caine, 1980; Gariano et al., 2015b; Peruccacci et al., 2017). The main advantage lies in the proximity of the rain gauge from the landslides, which provides a better relationship between rainfall and landslide triggering. However, the rainfall thresholds obtained in different rain gauges may be biased due to the different topographic and physiographic context characterizing each point of rainfall measuring. In these circumstances, the obtained rainfall thresholds will be biased by the differences regarding the rainfall regime of each location. Therefore, the merging and comparison of several rainfall datasets obtained in different places should be preceded by the normalization of rainfall data.

In addition, this type of analysis demands a high density of rain gauges network, which is only available for recent years. In Europe the number of stations increased after 1960 and had a peak between 1980 and 1990 (Haylock et al., 2008). In Portugal, a reliable rain gauge network only exists since 1980, when the mean distance between neighboring rain gauges was about 7.9 km (Belo-Pereira et al., 2011). Therefore, the use of multiple rain gauges to assess rainfall thresholds in the Lisbon region before 1980 would increase the threshold uncertainty due to the very low density of the available rain gauges. The restriction of the analysis to the period 1980 – 2010 was a possible alternative to overcome this limitation. However, this option was not considered because the number of landslide events would be drastically reduced (from 96 to 15 landslide events, Fig. 2), and the same would happen concerning the number of available rainfall events that did not generated landslides. The reduction of data representativeness would decrease the reliability of obtained rainfall thresholds.

Our landslide database covers a 145-year period (from 1865 to 2010) and we decided to analyse the complete period; thus, the selection of a single rain gauge was inevitable. The Lisboa-Geofísico rain gauge has uninterrupted rainfall measurements since 1864 and it is one of the few rain gauges in Portugal with long-term rainfall dataset. The comparable rain gauges (Évora, Porto, Guarda and Coimbra) are located more than 100 km distance from Lisbon. A long time series is an important condition to apply the return period and the Gumbel probability to the rainfall data. Moreover, this also provides a more reliable relation between the rainfall conditions and landslides, strengthening the reliability of the obtained thresholds. This is particularly important for a climate with a great variability, as the one existing in the study area.

5.3 Empirical definition of critical rainfall period

Identifying the rainfall responsible for the landslide occurrence is the basis for any empirical rainfall threshold calculation. A range of procedures to define the rainfall critical period associated to landslide events have been proposed in literature (e.g. Guzzetti et al. 2007; Segoni et al., 2014). Moreover, even the definition of critical rainfall is not straightforward. Aleotti (2004) defined the critical rainfall as the rainfall period starting when a shark increase in rainfall intensity is identified and ending when the first landslide is triggered. Therefore, in such circumstances, the cumulative rainfall before the rainfall increase is considered as antecedent rainfall and is not included in the critical rainfall. Brunetti et al. (2010) and Peruccacci et al. (2012, 2017) use the concept of "rainfall event", as a period of continuous rainfall separated by a dry period, with a seasonal variability concerning the length of the dry period (48 h in the dry season and 96 h in the wet season). In our study, the critical rainfall joints together the antecedent rainfall (acting as a landslide preparatory factor) and the rainfall that triggered the landslide event. Our procedure to define the critical rainfall combination, responsible for preparing/triggering the landslide event is based on the return period calculation, by selecting the cumulative rainfall with the highest return period.

This approach has the advantage of being an objective method easily reproducible to other areas and provides rainfall thresholds with the most optimistic results concerning the ROC metrics. However, the use of the return period implies a 'rigid' statistical relationship between the rainfall and landslides, which does not always occur. Moreover, in some cases, the

cumulated rainfall associated to the landslide triggering is not very high. However, the use of other empirical procedure, as the previous mentioned, to define the critical rainfall period are based on subjective decisions, like the duration of the dry period to bound the rainfall events.

Probably, the identification of the critical rainfall period for a specific landslide event is only possible to determine with precision using coupled geotechnical and transient hydrological physical models. However, each slope is a unique system and the rainfall is not uniform both in time and space, which explain the difficulty to establish rainfall thresholds based on physically-based models at the regional scale.

5.4 Identification of landslide rainfall-triggered events

The uncertainty related with the triggering factor is particularly high when newspapers are the main source of information and, additionally, when a long time series is been analysed. As a rule, only newsworthy content are reported by newspapers, which certainly create bias in the landslide database. For instance, landslides that generated human damage or occurred in urban environment are usually highlighted, which increases the probability of landslides triggered by human action to be included in the database, despite its exclusion whenever a description suggest an anthropic intervention. On contrary, landslides triggered by rainfall that did not generate any social or economic damage were probably unreported by newspapers. In addition, the long time elapsed since the occurrence of some landslides inhibits the use of recent methods and techniques to confirm the rainfall triggering. For example, the confirmation of landslide events using aerial photo interpretation is only possible in Portugal for the period after 1947.

Using field-based landslide inventories in the Lisbon Region, Zêzere et al. (2015) considered as rainfall-triggered landslide event any date for which at least five individual landslides are known to have occurred on natural slopes. This criterion reduces the possibility of inclusion of landslide triggered by human action. However, this criterion cannot be used in the present study, because landslides reported in newspapers are certainly a small sample of total triggered landslides. Therefore, any reported date, even those reporting a single landslide, should be admitted as a 'landslide event candidate'. Addressing the issue of the triggering factor, those landslide events associated to rainfall combinations (cumulated rainfall-duration) with return period below 3 years were rejected as rainfall-triggered. Using field-based landslide inventories in the Lisbon Region, Zêzere et al. (2015) showed that only 12% of landslide events triggered by rainfall have cumulated rainfall return period below 3 years and landslide events were not registered with rainfall conditions with return period below 2 years. Given our data source feature (based in newspaper) and our study area (integrated in an urban area) a more conservative boundary was preferred, and therefore, the selection of 3 years-return period.

This criterion can eventually eliminate some (few) landslide events triggered by rainfall in the study area. However, the possibility to include non-rainfall triggered landslide events would increase, not applying this criterion. The inclusion of non-rainfall triggered landslides in the analysis would bias the rainfall thresholds as well as the ROC metrics, generating a higher number of undesirable false alarms.

This criterion proved to be suitable to distinguish between rainfall events that triggered and did not trigger landslide events in the study area. However, further investigation should be made on this topic, namely in other study areas. An alternative method, to the 3-year return period criterion could be the calculation of the thresholds in the range 5 - 10 km, thus excluding the current urban area. However, the landslide database used in this analysis covers a very large time period (145 years) and the urban area extension did change considerably. For example, at the end of the 19th century extensive rural zones were present within the 5 km buffer. Moreover, this option would reduce the number of landslide events considered in the analysis from 96 to 37, which would reduce the reliability of the obtained rainfall thresholds.

5.5 The spatial representativeness of a rain gauge data series

The discussion on the spatial representativeness of a rain gauge data series used to assess rainfall thresholds for landslide activity is scarce in literature, which is surprisingly taking into consideration the large number of papers dealing with empirical rainfall thresholds published in recent years. In previous work using multiple rain gauges, the distance between the gauge and the landslides is the criterion used to select the rain gauge, along with setting features (e.g. elevation difference and morphological settings) (e.g. Brunetti et al., 2010; Peruccacci et al., 2017), however the discussion on the topic is scarce and different distances have been proposed for the same region. For instance, for the Calabria region (Italy) Vennari et al. (2014) used 12 km as limit distance, whereas Gariano et al. (2015b) used 5 km.

To the best of our knowledge the spatial representativeness of a single rain gauge used to assess rainfall thresholds was never addressed before. In this work, we applied a method to compute the critical distance based on the ratio of non-rainfall triggered landslide events and rainfall-triggered landslide events tested along several buffer zones starting from the rain gauge at 5, 10, 15, 20, 30, 40, 50 and 60 km distance. Our method takes in account both the source of landslide data (newspapers) and the location of the rain gauge in the urban area. We acknowledge that this method is valid in urban areas, as is the case of the Lisbon region, and can be applied in other zones with similar context. However, the method cannot be directly applied in non-urban areas, which is a drawback.

In addition, an effort was made to evaluate the regional performance of the lower limit threshold, which was proved to be applied with reasonable results up to 50 km distance from the rain gauge. It should be pointed out, that the climatic and topographic features of the study area allow for the spatial enlargement of the threshold. The rainfall regime of the region is spatially consistent and it is mainly influenced by the atmospheric general circulation and by the oceanic proximity, with the same weather types associated with high rainfall (Trigo and DaCamara, 2000; Ramos et al., 2014). In addition, the orographic effect on the rainfall distribution is low in the region, which enlarges the spatial representativeness of the reference rain gauge. However, the distance where the thresholds can be applied will be always connected with high levels of uncertainty associated to the rainfall discontinuity both in space and time. Therefore, the consideration of the lower limit threshold up to 50 km should be used only where no other threshold is available.

6. Conclusion

The definition of rainfall thresholds for landslide initiation is typically characterized by uncertainty, which makes the use of probabilistic approach highly recommended (e.g. Frattini et al., 2009; Berti et al., 2012). In this study a comprehensive method to assess the rainfall thresholds was applied using a centenary database of landslides occurred in the Lisbon region, from 1865 to 2010, combined with a rainfall dataset collected at the Lisboa-Geofísico rain gauge, with uninterrupted daily measurements since 1864. The identification of the critical rainfall combinations responsible for preparing and triggering the landslide events were identified by selecting the pairs (cumulated rainfall-duration) with the highest return period. Rainfall events that did not generate landslides were also selected and included in the analysis.

The use of a single rain gauge to assess rainfall thresholds implies the definition of the geographical area where the thresholds can be applied. In this study we demonstrated that 10 km is the optimal distance to compute the rainfall thresholds, although these may be spatially extended with enough confidence up to 50 km. These distances are controlled by the climatic and physiographic characteristics of the study area and should not be directly extrapolated to other study areas.

The zone between the lower limit and the upper limit thresholds (where landslide events may occur) was analyzed following a probabilistic approach, based on the Positive Predictive rate. Therefore, a range of probabilities of landslide event were established associated to five intermediate thresholds (20 %, 30 %, 40 %, 50 % and 60 %), which allow quantifying the uncertainty. Additionally, the performance of each threshold was assessed using ROC metrics. This approach can be used within landslide early warning systems as different alert levels can be associated to different probabilities of landslide occurrence. Future research should be focused on the validation and application of the thresholds in a prototypal landslide early warning system, as already made in other areas (e.g. Tiranti and Rabuffetti, 2010; Calvello et al., 2015; Segoni et al., 2015; Piciullo et al., 2017).

The probability of exceedance of any rainfall event combined with the probability of landslide occurrence given rainfall exceeding the threshold was also calculated. This information can be more informative to the decision makers responsible for spatial planning, although additional information is needed regarding the landslide magnitude and the spatial distribution of future landslides.

The probabilistic approach used in this study is based on very long time series of landslide events and rainfall measurements, which are seldom available. This is a serious constrain to the application of the method to other study areas where long time series of landslide events and rainfall measurements are not available. In any case, the use of landslide inventories covering long time periods is crucial to obtain reliable thresholds valid at the regional scale.

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Table 1. ROC metrics (according to Staley et al., 2013).

	Formulation	Optimal value
True Positive rate (TP_r)	$TP_R = \frac{TP}{TP + FN}$	1
False Positive rate (FP_r)	$FP_R = \frac{FP}{FP + TN}$	0
False Alarm rate (FA_r)	$FA_R = \frac{FP}{TP + FP}$	0
Threat Score (TS)	$TS = \frac{TP}{TP + FN + FP}$	1

Table 2. Ratio of non-rainfall triggered landslide events / rainfall-triggered landslide events for different buffer distance to the reference rain gauge.

Distance to the rain gauge (km)	Non-rainfall triggered landslide events (a)	Rainfall triggered landslide events (b)	Ratio (a/b)
5	51	78	0.65
10	60	96	0.63
15	67	101	0.66
20	69	105	0.66
30	78	117	0.67
40	86	125	0.69
50	88	128	0.69
60	92	131	0.70

Tabela 3. ROC metrics associated to rainfall thresholds and intermediate thresholds for landslide events in the Lisbon region.

		Equations	TP	FN	FP	TN	TP_r	FP_r	Far	TS	PP_r
Regression threshold (linear)		R = 5.5D + 124.6	38	58	34	1394	0.40	0.02	0.47	0.29	0.53
Regression threshold (potential)		R = 67.8D0.46	39	57	48	1380	0.41	0.03	0.55	0.27	0.45
Lower limit threshold		R = 4.4D + 56.5	96	0	527	901	1	0.37	0.85	0.15	0.15
Upper limit threshold		R = 7.3D + 235.8	3	93	0	1428	0.03	0	0	0.03	1
Intermediate thresholds	PP_r 20 %	R = 4.6D + 68.0	91	5	364	1064	0.95	0.25	0.80	0.20	0.20
	PP_r 30 %	R = 4.8D + 84.8	76	20	177	1251	0.79	0.12	0.70	0.28	0.30
	PP_r 40 %	R = 5.1D + 98.2	66	30	99	1329	0.69	0.07	0.60	0.34	0.40
	PP_r 50 %	R = 5.3D + 113.0	50	46	50	1378	0.52	0.04	0.50	0.34	0.50
	PP_r 60 %	R = 6.2D + 164.1	15	81	10	1418	0.16	0.01	0.40	0.14	0.60

Table 4 Ratio FN/(TP+FN) considering the lower limit rainfall threshold for different buffer distances to the rain gauge.

Distance (km)	True Positive (TP)	False Negative (FN)	Ratio FN/(TP+FN)
[10-15[	20	4	0.167
[15-20[	7	2	0.222
[20-30[	26	11	0.297
[30-40[	23	7	0.233
[40-50[	8	2	0.200
[50-60[	5	5	0.500

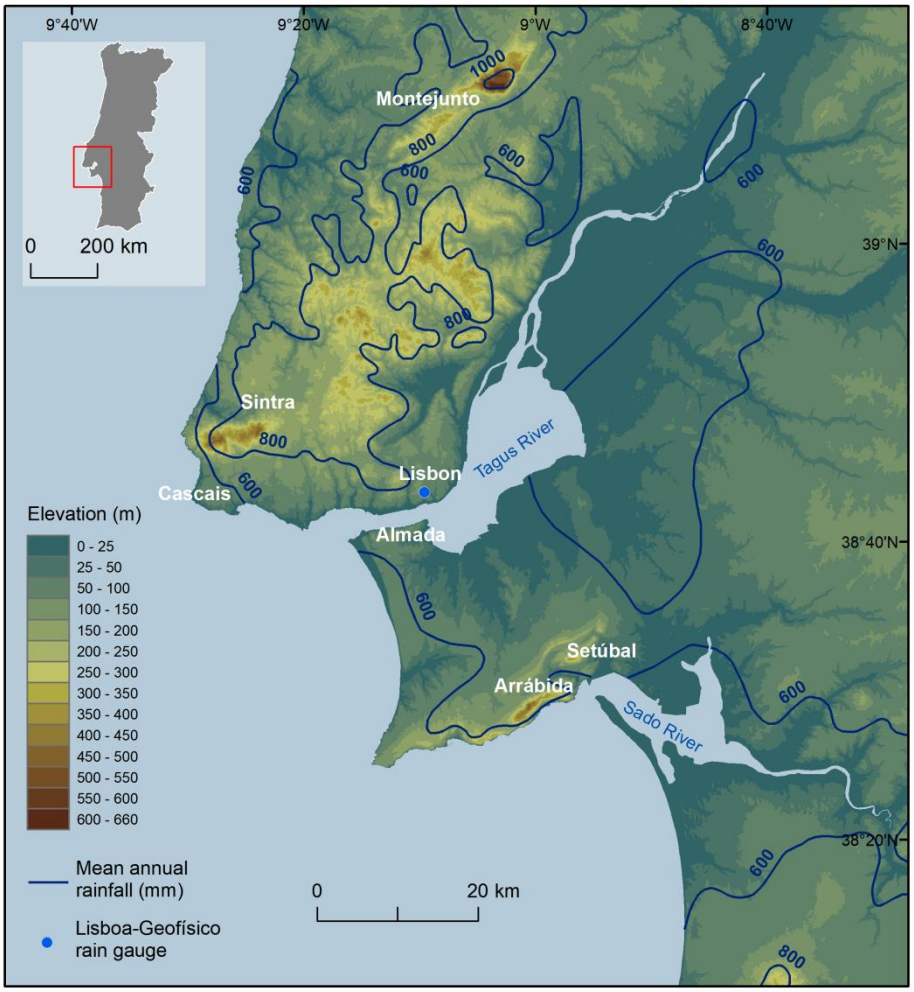

Figure 1. Elevation and mean annual rainfall in the study area (source: Daveau et al., 1977).

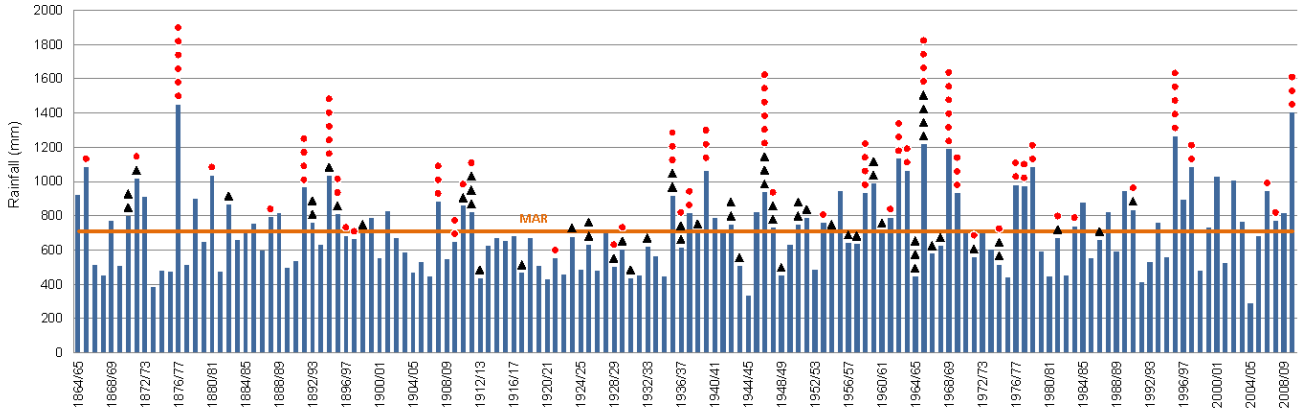

Figure 2. Annual rainfall (climatological year: September to August) at Lisboa-Geofísico rain gauge for the period 1864/65 - 2009/10. Orange line symbolizes the mean annual rainfall (MAR); red dots and back triangles symbolize rainfall-triggered landslide events and non-rainfall triggered landslide events, respectively, at the distance up to 10 km from the reference rain gauge.

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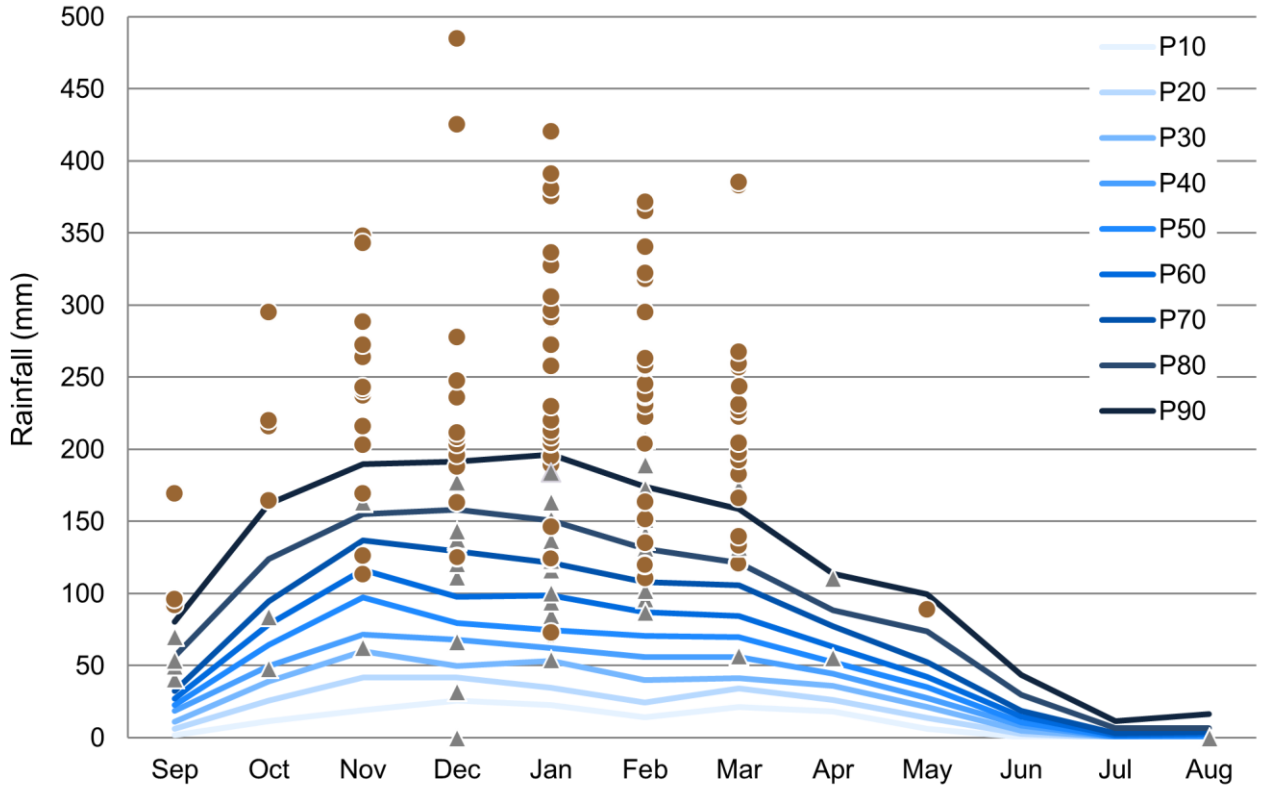

Figure 3. Monthly rainfall percentiles at Lisboa-Geofísico rain gauge for the period 1864/65 - 2009/10. Brown dots and grey triangle symbolize the 30-day cumulative absolute antecedent rainfall for rainfall-triggered landslide event and for non-rainfall triggered landslide event, respectively, at the distance up to 10 km from the reference rain gauge.

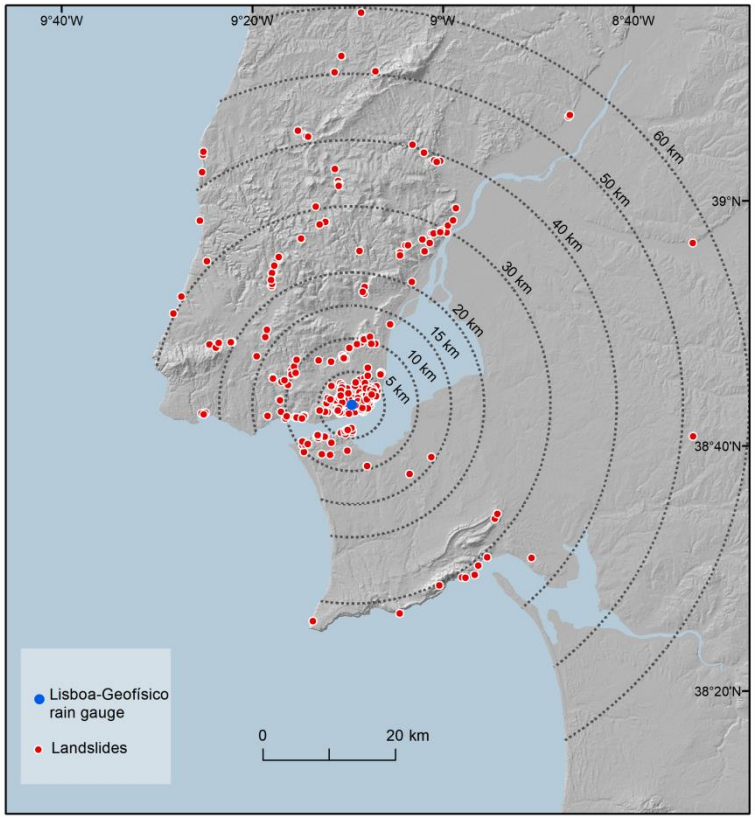

Figure 4. Distribution of landslides in the Lisbon region (1865/2010) and buffer-distances from the reference rain gauge.

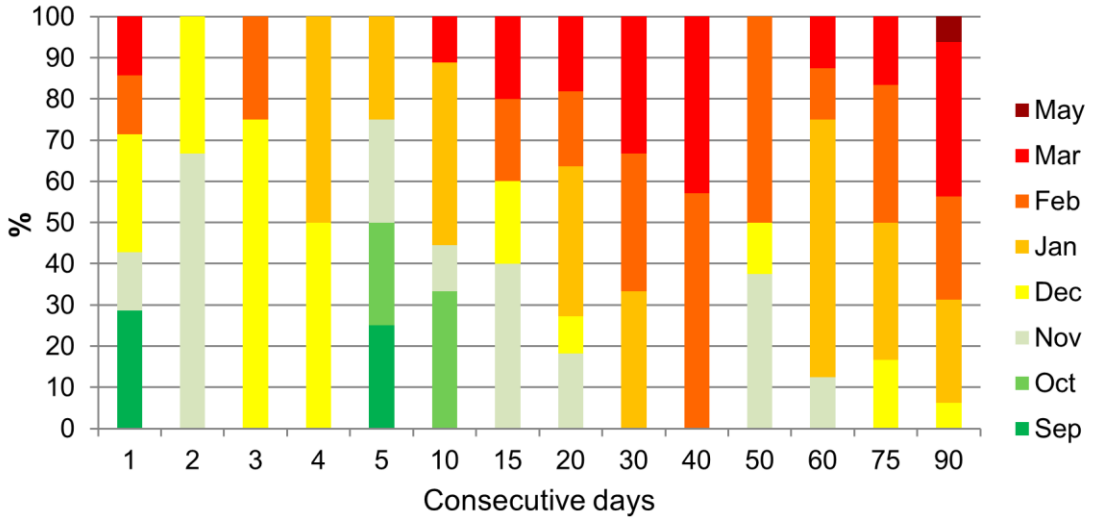

Figure 5. Monthly frequency of the rainfall-triggered landslide events according to the duration of the rainfall period.

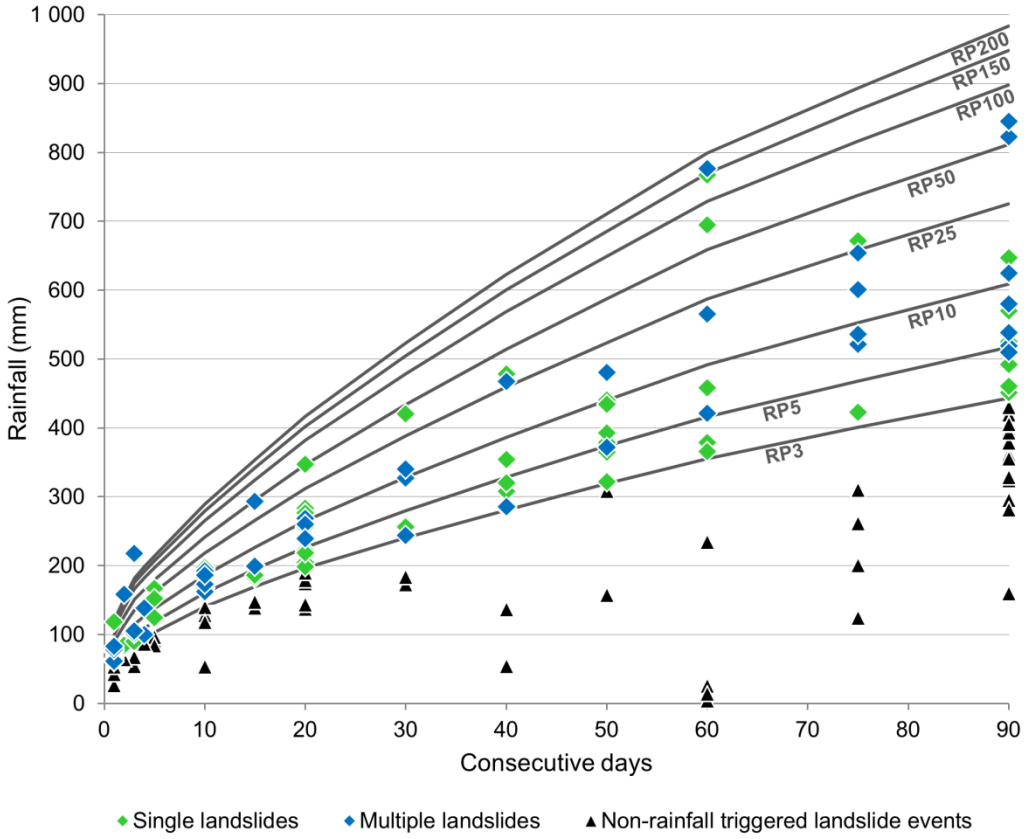

Figure 6. Critical combination cumulated rainfall–duration that resulted in landslide events (single and multiple landslides) and Return Period (RP) for 3, 5, 10, 25, 50, 100, 150 and 200 years. Distance up to 10 km from the reference rain gauge. The non-rainfall triggered landslide events identified are also represented.

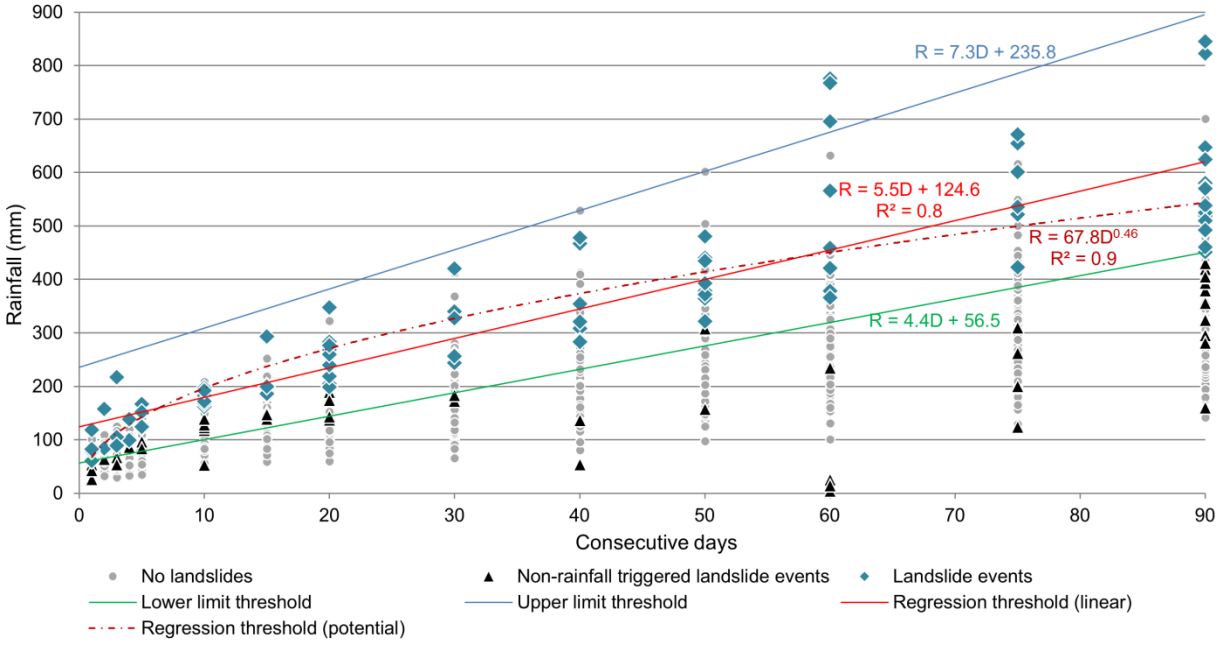

Figure 7. Cumulated rainfall–duration thresholds for landslide events in the Lisbon region (1865 to 2010). Distance up to 10 km from the reference rain gauge.

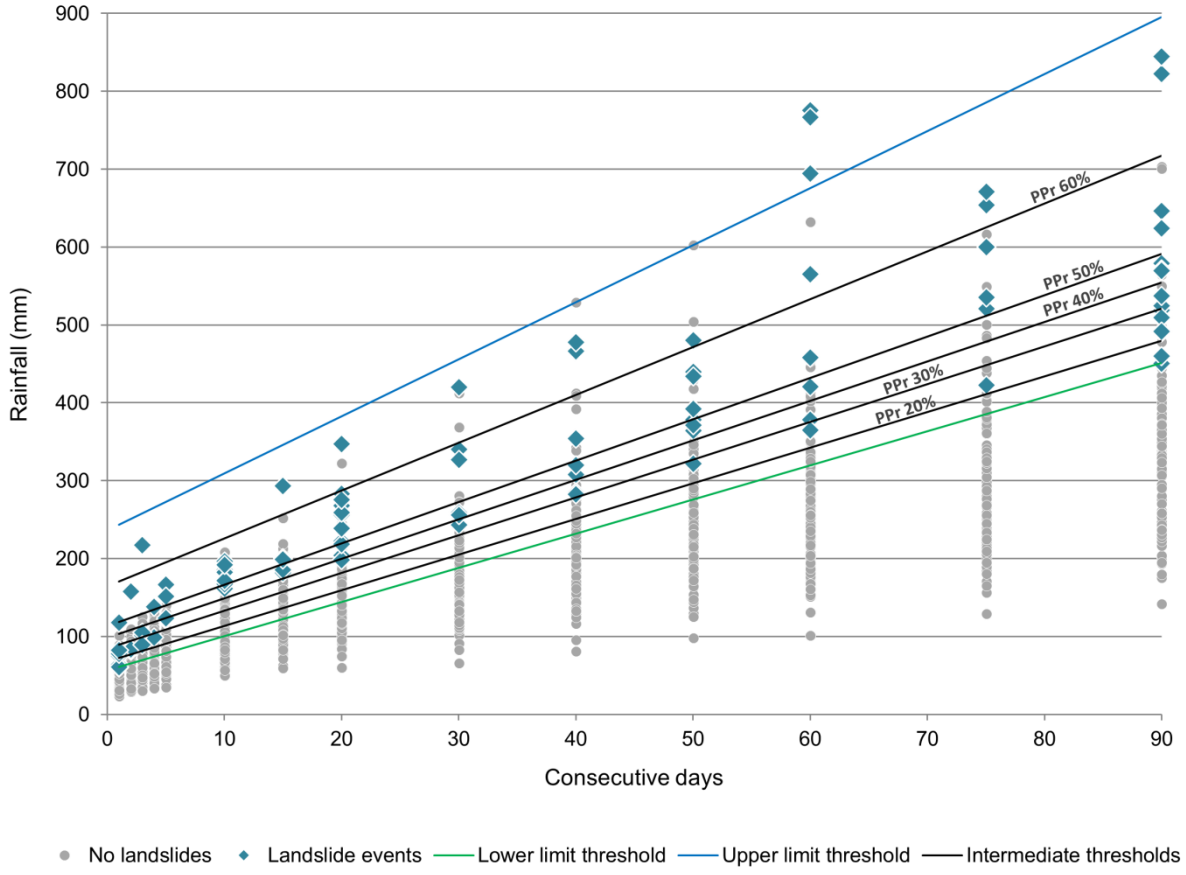

Figure 8. Intermediate thresholds based on the probability of landslide events (20 %, 30 %, 40 %, 50 % and 60 %) in the zone between the lower limit threshold and the upper limit threshold.

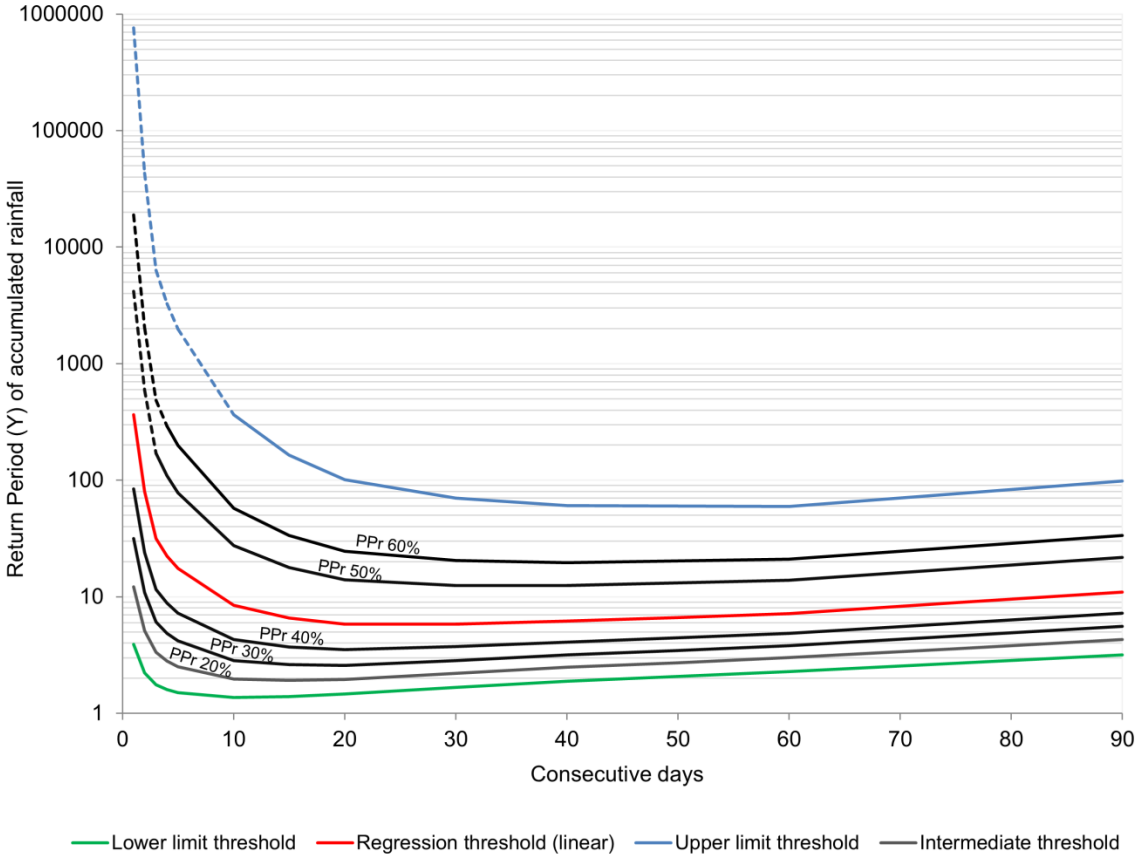

Figure 9. Return period of rainfall thresholds computed for the Lisbon region (linear regression, lower limit, upper limit and intermediate thresholds PP_r 20 %, PP_r 30 %, PP_r 40 %, PP_r 50 %, and PP_r 60 %). Dashed lines represent conditions never registered in the rain gauge.