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Rainfall thresholds for the triggering of landslides considering previous soil moisture conditions (Asturias, NW Spain)

Abstract Given its geological and climatic conditions and its rugged orography, Asturias is one of the most landslide prone areas in the North of Spain. Most of the landslides occur during intense rainfall episodes. Thus, precipitation is considered the main triggering factor in the study area, reaching average annual values of 960 mm. Two main precipitation patterns are frequent: (i) long-lasting periods of moderate rainfall during autumn and winter and (ii) heavy short rainfall episodes during spring and early summer. In the present work, soil moisture conditions in the locations of 84 landslides are analysed during two rainfall episodes, which represent the most common precipitation patterns: October–November 2008 and June 2010. Empirical data allowed the definition of available water capacity percentages of 99–100% as critical soil moisture conditions for the landslide triggering. Intensity-duration rainfall thresholds were calculated for each episode, considering the periods with sustained high soil moisture levels before the occurrence of each analysed landslide event. For this purpose, data from daily water balance models and weather stations were used. An inverse relationship between the duration of the precipitation and its intensity, consistent with published intensity-duration thresholds, was observed, showing relevant seasonal differences.

Keywords Landslide · Rainfall · *I-D* threshold · Soil moisture · Asturias

Introduction

Rainfall-induced landslides are one of the most widespread slope instability phenomena (Guzzetti et al. 2008) posing a serious risk to public safety worldwide (Baum and Godt 2010) so that their temporal prediction is of great interest to establish effective warning systems (Segoni et al. 2009). At a local scale, many authors have used hydrological-geotechnical approaches to model the physical processes involved in landslide triggering (infiltration, sub-surficial flow, pore water pressure) (Iverson 2000; Brooks et al. 2004; Amaral et al. 2009). However, the uncertainty linked to the spatio-temporal variation of those factors together with the difficulty to obtain reliable sustained measurements hampers the implementation of those models over large areas (Martelloni et al. 2012; Posner and Georgakakos 2015).

At a regional scale, statistical approaches are widely used to calculate thresholds, which represent the rainfall or soil moisture conditions that must be reached or exceeded for the landslide triggering on the basis of empirical observation (Guzzetti et al. 2007). Usually, the calculation of the thresholds is based on the study of individual or multiple rainfall events that resulted in landslides in the past. These critical rainfall conditions are described through different parameters; the combination of rainfall intensity and duration is one of the most commonly considered

(Guzzetti et al. 2007, 2008; Dahala and Hasegawa 2008; Brunetti et al. 2010). Other indicators are also used, such as accumulated rainfall (Cardinali et al. 2006) or accumulated rainfall-duration (Peruccacci et al. 2012; Gariano et al. 2015). However, those approaches ignore the crucial role of previous soil moisture conditions (Segoni et al. 2009; Baum and Godt 2010). Some authors estimate soil moisture taking into account antecedent precipitation indices over a long period before the occurrence of the landslide (Crozier 1999; Glade et al. 2000; Zêzere et al. 2015).

Given the scarcity of in situ soil moisture measurements, hydrological balance simulations have been up to now the most usual method to develop soil moisture models at a regional scale. Precipitation data series and soil characteristics are the input data of those models, whose implementation makes it possible to consider previous soil wetness conditions in the calculation of the thresholds (Posner and Georgakakos 2015). Presently, satellite remote sensing technology can provide accurate soil moisture data at regional and global scales (Gruhier et al. 2010), becoming an alternative to modelled soil moisture data (Ray et al. 2010). However, satellite data show large estimation uncertainties, especially in mountainous and heavily vegetated areas (Temini et al. 2010).

Precipitation is also the most widespread natural triggering factor in the Iberian Peninsula (Corominas et al. 2005). Nevertheless, despite the large social and economic impacts caused by rainfall-induced landslides in Spanish mountainous areas (Bonaechea et al. 2014), little work has been conducted on the temporal forecasting of landslides. Among these, the accumulated rainfall values calculated for Asturias (Domínguez-Cuesta et al. 1999, 2012) and País Vasco (Díaz et al. 2012), the accumulated rainfall-duration thresholds defined for the Eastern Pyrenees (Corominas and Moya 1999) and the intensity-duration thresholds defined for the Pyrenees (Corominas et al. 2002, 2005), the Spanish Central System (Ruíz-Villanueva et al. 2011) and Cantabria (San Millán Revuelta 2015) can be mentioned.

The main goal of the present work is to calculate rainfall intensity-duration thresholds for the occurrence of landslides through the statistical analysis of two rainfall episodes representative of the main precipitation patterns in the Principality of Asturias (November–December 2008 and June 2010), taking into account the previous soil moisture conditions for the region.

Study area

Principality of Asturias is an autonomous community from the NW of Spain with an extent of 10,603.57 km². Bordered to the south by the Cantabrian Range and to the north by the Cantabrian Sea, the area constitutes an E-W trending strip of territory characterised by a mountainous relief, with its highest point rising to 2648 m asl (Fig. 1). The bedrock consists of folded and fractured Palaeozoic rocks (Marcos

2004; Alonso et al. 2009) overlaid in the north and east of the region by a discordant Mesozoic and Tertiary cover (Alonso et al. 1996). The elevation of the Cantabrian Range during the Alpine Orogeny conditioned the development of the present relief, which has been modified through fluvial incision (Jiménez-Sánchez et al. 2014), karst processes (Ballesteros et al. 2015) and glacial activity (Rodríguez-Rodríguez et al. 2015) during the Quaternary. Together with fluvial and coastal processes, slope instabilities are the most widespread phenomenon of the current geomorphological evolution in the area. Because of the high density and scattering of the population in this region, landslides cause every year great economic losses and sometimes claim human victims.

Previous research (Domínguez-Cuesta et al. 1999, 2012; Valenzuela et al. 2017) pointed to precipitation as the main triggering factor of landslides within the study area. Due to the proximity to the sea and to the Cantabrian Range, the orientation of the major geographical features (ranges and valleys) and the prevailing winds, the orographic effect plays a predominant role in the rainfall distribution over the Asturian region. Other precipitation mechanisms are also present, such as frontal precipitation associated with mid-latitude cyclones and convective precipitation associated with the instability of air masses. Two main precipitation patterns are the most frequent: (i) long-lasting frontal rain associated with autumn and winter low pressure systems or orographic rain due to northern maritime air masses and (ii) short-lasting heavy rainfall episodes, due to a strong instability of air masses during spring and early summer. Average annual precipitation in Asturias is 960 mm (Oviedo weather station, period 1981–2010) (AEMET 2012), and average monthly precipitation shows maximum and minimum values in autumn and summer, respectively. Average annual number of rainy days ranges from 123 (> 1 mm in 24 h) to 30 days (> 10 mm in 24 h) and 4 days (> 30 mm in 24 h), resulting in frequent and meaningful wet periods (Botey et al. 2013). All the aforementioned contribute to maintaining high soil moisture levels through long periods, favouring the landslide triggering in Asturias, which is considered an initial hypothesis for the present study.

Methodology

Selection of the landslide events

Empirical data used for the present work come from the BAPA: Base de datos de Argayos del Principado de Asturias-Principality of Asturias landslide database (<http://geol.uniovi.es/BAPA>), a landslide inventory which gathers information extracted from press archives and reports from citizens and institutions. All the landslides gathered within this inventory are classified into three categories taking into account the accuracy of its spatio-temporal location: levels 1, 2 and 3 (Valenzuela et al. 2017).

The first step in this work was the selection of two periods recorded in the BAPA database which (i) show a high concentration of landslides and (ii) are representative of the main precipitation patterns in the region. For the present analysis, only those records with the highest level of spatio-temporal accuracy (level 1: exact date and coordinates) were considered. Then, available information about the triggering factors of the selected landslides was reviewed in order to remove those with an origin different from rainfall, such as fluvial erosion, coastal erosion or human

causes. Finally, a revision of the information about the type of slope instability (landslide, flow, rockfall) and the characteristics of the affected slope (natural or artificial) was conducted over the selected records. Each individual landslide within the selected periods was considered as a landslide event.

Analysis of the climatic and soil moisture conditions

A characterisation of the average meteorological conditions during the selected periods was carried out through the use of data from the National Oceanic and Atmospheric Administration of the EEUU (NCAR/NCEP Reanalysis 1). Sea level pressure and 500 hPa geopotential height, expressed in hectopascals and meters, respectively, represent the atmospheric pressure on the surface and the height of the isobaric surface defined by all the points with a pressure of 500 hPa; both parameters are used to define the presence of high (H) and low (L) pressure systems that condition the arrival of frontal systems affecting the study area. Moreover, temperature values corresponding to the 500 and 850 hPa isobaric surfaces and expressed in degree Celsius are used to determine the influence of cold or warm air masses over Asturias.

Hereafter, a daily comparison between the selected landslide events and precipitation and soil moisture records was performed considering both the months in which the landslide events occurred and the previous one. Daily precipitation records cover a measuring period from 7 a.m. of the given day to 7 a.m. of the following one; however, landslide records are temporally located considering calendar days. Thus, when data about the time of the landslide occurrence was available, its date was reviewed to match both sets of data in temporal terms.

Available water capacity (AWC), usually interpreted as the amount of pore water that may be stored in a soil and may be available for growing plants, was the hydrological index chosen to represent the soil moisture conditions (Bruand et al. 2003; Julia et al. 2004). AWC data used for the present work have been calculated as a percentage of the maximum pore water storing capacity (total available water capacity) of a soil volume limited by the depth of the vegetation roots. Data were extracted from daily water balance models developed by Agencia Estatal de Meteorología-Spanish Meteorological Agency (AEMET) for the Spanish territory (Botey and Moreno 2012). Input data considered for the modelling are as follows: (i) daily precipitation and insolation values from weather stations (from 06 to 06 Z); (ii) atmospheric pressure, temperature, relative humidity and wind speed data from HIRLAM weather forecast model (Unden et al. 2002); (iii) soil type and texture, regarding the NRCS-USDA Soil Taxonomy (NRCS-USDA 2003); (iv) depth of the vegetation roots, following the land uses database Corine Land Cover (IGN 2006) and (v) slope values. Output data are continuous models in raster format (25 km² cell size) obtained using kriging interpolation.

A comparison between precipitation data from two different sources was performed: (i) daily precipitation models in raster format (25 km² cell size) from AEMET daily water balance models (Botey and Moreno 2012) and (ii) daily precipitation data series from the nearest AEMET weather station to each landslide. For each landslide location, the use of the software ArcGIS 9.3 enabled the selection of the closest AEMET weather station and the extraction of daily precipitation and soil moisture (AWC) values from raster models, showing the evolution of those parameters at least 1 month before the landslide occurrence.

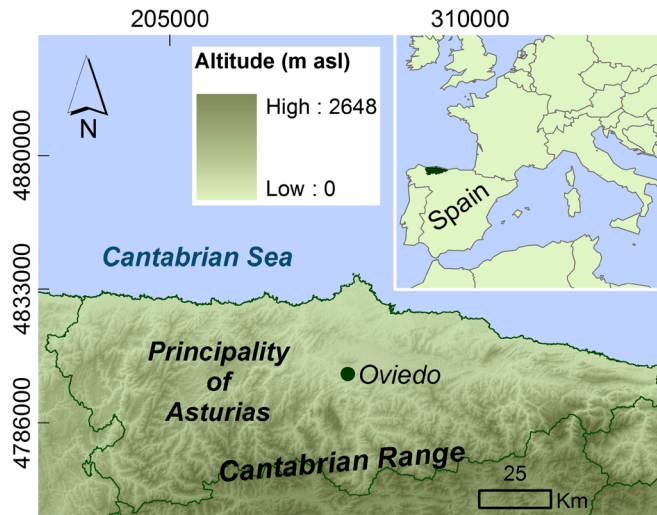


Fig. 1 Location of the study area

Statistical analysis

Several intensity-duration (I-D) thresholds were calculated to determine the probability of occurrence of landslides; for this purpose, data from the two precipitation data sources were used. The followed methodology was modified from Brunetti et al. (2010). These authors established a minimum period without precipitation to define the beginning of the rainfall-triggering event. In contrast, the methodology proposed in this work introduces the use of the previous soil moisture conditions to define the D parameter. Critical soil moisture levels for the triggering of slope instabilities were defined considering the AWC values of the soil in the days and locations of the recorded landslide events. Thus, D was calculated as the period of days with critical AWC values before the occurrence of a landslide. After defining this parameter, the rainfall mean intensity I (mm h^{-1}) was calculated by dividing the accumulated rainfall (mm) in the considered duration D by the length of this same period (hours).

The frequentist approach described by Brunetti et al. (2010) was adopted in the present research and conducted by the use of the software R-UAC-3.2.0. The threshold curve is assumed to be a power law:

$$I = \alpha D^{-\beta}$$

where I is the rainfall mean intensity (mm h^{-1}), D is the previous period with critical soil moisture levels (h), α is the intercept and β defines the slope of the power law curve. Empirical data were log-transformed to calculate the best-fit line by means of a linear equation $\log(I) = \log(\alpha) - \beta \log(D)$, equivalent to that described above. Residuals were determined as the difference between the logarithm of the empirical I value and the corresponding theoretical I value of the best-fit line. Then, the probability density function of this distribution was calculated through Kernel density estimation, by using a Gaussian fit. On the basis of this probability density function, different α values were calculated for different probabilities of occurrence of landslides, producing threshold parallels to the best-fit line for a probability of occurrence of 5, 25, 50 and 75%.

Results

November–December 2008 and June 2010 are the months with the highest number of landslide records within the BAPA database and constitute good examples of the most frequent precipitation patterns described for the study area. Consequently, present analysis focuses on these two periods, also including the previous month in each case. BAPA database provided 139 landslide records for the period between October 1, 2008, and December 31, 2008, hereinafter “2008 period” (Fig. 2), and 164 landslide records for the period between May 1, 2010, and June 30, 2010, hereinafter “2010 period” (Fig. 3). After the removal of the records with low levels of spatio-temporal accuracy and triggers different from rainfall, 43 landslides in the first case and 41 landslides in the second case were considered suitable for the analysis (Fig. 2a and Fig. 3a). In the 2008 period, 4 out of the 43 slope instabilities were classified as flow, 9 as slide, 13 as rockfall and the remaining 17 could not be classified due to the scarcity of data (Fig. 2b). In the 2010 period, 5 out of the 41 slope instabilities were classified as flow, 5 as rockfall, 16 as slide and the remaining 15 were undetermined (Fig. 3b). In both cases, a high percentage of the landslides took place in artificial slopes (46.5% in the 2008 period and 34.2% in the 2010 period) while a small percentage took place in natural slopes (9.3% in the 2008 period and 26.8% in the 2010 period); in both cases, the type of slope in the remaining percentage was undetermined (Fig. 2c and Fig. 3c).

The characterisation of the average synoptic meteorological conditions during the 2008 period showed the succession of several frontal systems associated with mid-latitude low pressure systems moving eastward and the subsequent incursion of a polar air mass. This atmospheric synoptic pattern produced strong NW winds, low temperatures and a long-lasting period of almost continuous precipitation, from October 20, 2008, to December 16, 2008, with rainfall gaps of 1 to 5 days (Fig. 2d). Likewise, the analysis of the 2010 period showed the presence of a quasi-stationary low pressure system centred over the Cantabrian Sea and the development of a mid-level cold air pool, which gave rise to strong thermal and dynamic instability. This pattern resulted in

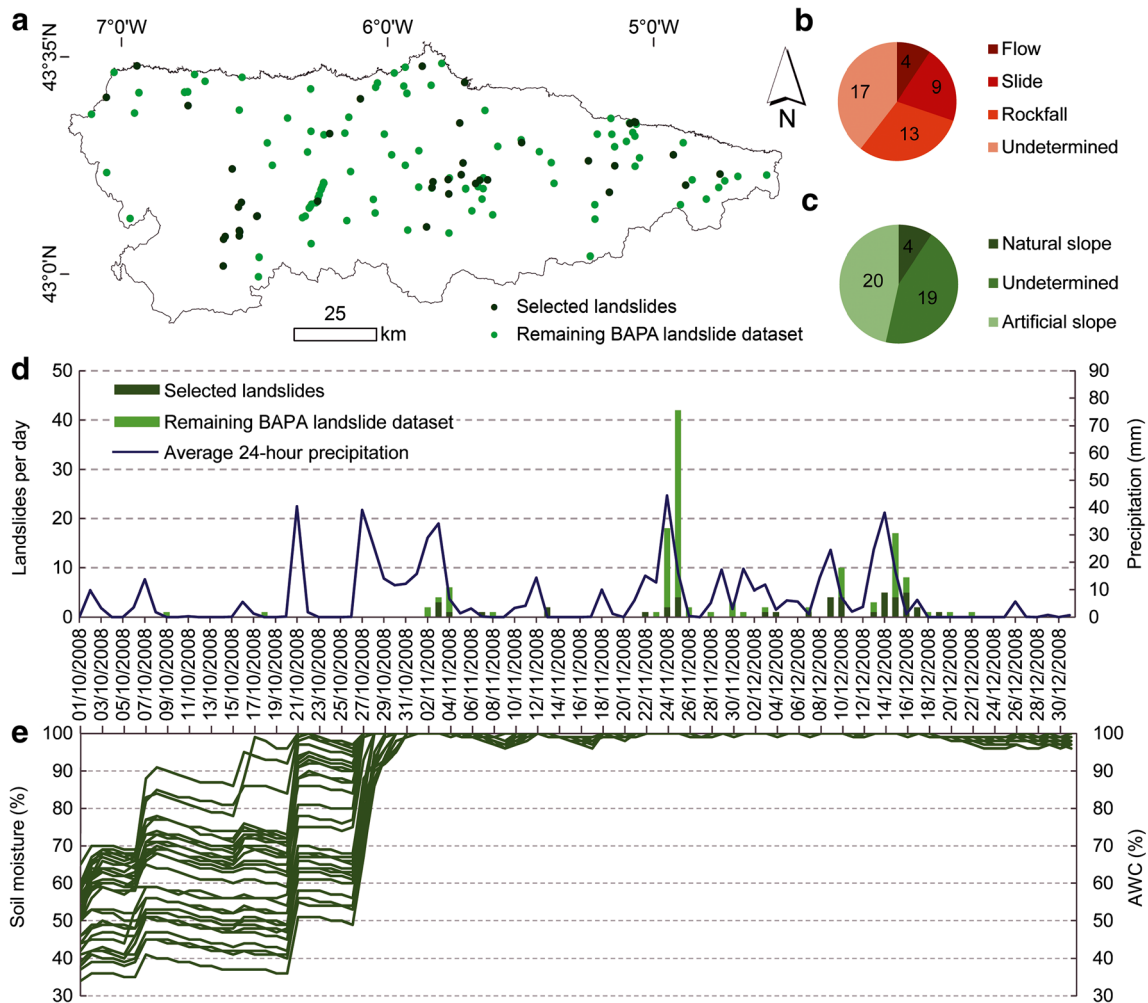


Fig. 2 A spatial location of the landslides from the BAPA database recorded for the 2008 period, differentiating those ones selected for the analysis; b type of landslide; c type of slope; d temporal distribution of the landslide records (differentiating those ones selected for the analysis) for the 2008 period and its relation to average 24-h precipitation values for the location of the selected landslides (extracted from AEMET water balance models; Botey and Moreno 2012); e evolution of the soil moisture conditions, expressed in percentage of AWC, for each selected landslide location during the 2008 period

two short-lasting and convective rainfall episodes between October 8, 2010, and October 16, 2010 (Fig. 3).

Figures 2 and 3 represent the spatial and temporal distribution of the total number of landslides identified during the 2008 and 2010 periods, differentiating those landslide events selected for this study. Both graphics show the relation between the temporal occurrence of the landslides, the daily soil moisture conditions and the average 24-h precipitation, considering the values extracted from water balance models raster outputs for all the locations of the selected landslides.

In both periods of study, the days with a high number of landslide records are coincident with high values of average 24-h precipitation. This is the case of the 60 landslides recorded during the 24th and 25th of November 2008, when a precipitation event reaching average daily values of 44 mm took place (Fig. 2d). The same correlation is also observed during the 2010 episode, when 45 and 68 landslides were recorded during two precipitation events occurred between the 9th and the 11th of June (177 mm in 3 days) and the 15th of June (45 mm),

respectively (Fig. 3d). However, no landslides were reported in some days with significant precipitation values, such as the October 21, 2008, the October 27, 2008 (Fig. 2d) or the period between May 10, 2010, and May 15, 2010 (Fig. 3d).

Precipitation during the 2008 period is characterised by moderate intensity, reaching absolute rainfall values in 24 h below 104 mm. After the first relevant rainfall episode (October 21, 2008), soil moisture in the landslide locations showed a slow steady rise, spending between 7 and 11 days to reach the 100% of AWC (Fig. 2e). Following this, the almost sustained rainfall (only interrupted by 1–4 day periods without precipitation) (Fig. 2d) allows to maintain values of AWC between 96 and 100% during periods of 50–55 days, depending on each location. In the case of the 2010 period, the heavy-intensity precipitation recorded, with absolute maximum values of 188 mm in 24 h, set up a sudden soil moisture rise that reached the 100% of AWC in 1–4 days. After the beginning of the first precipitation event (June 8, 2010) (Fig. 3d), soil maintained values of AWC between 97 and 100% during 5–7 days (Fig. 3e).

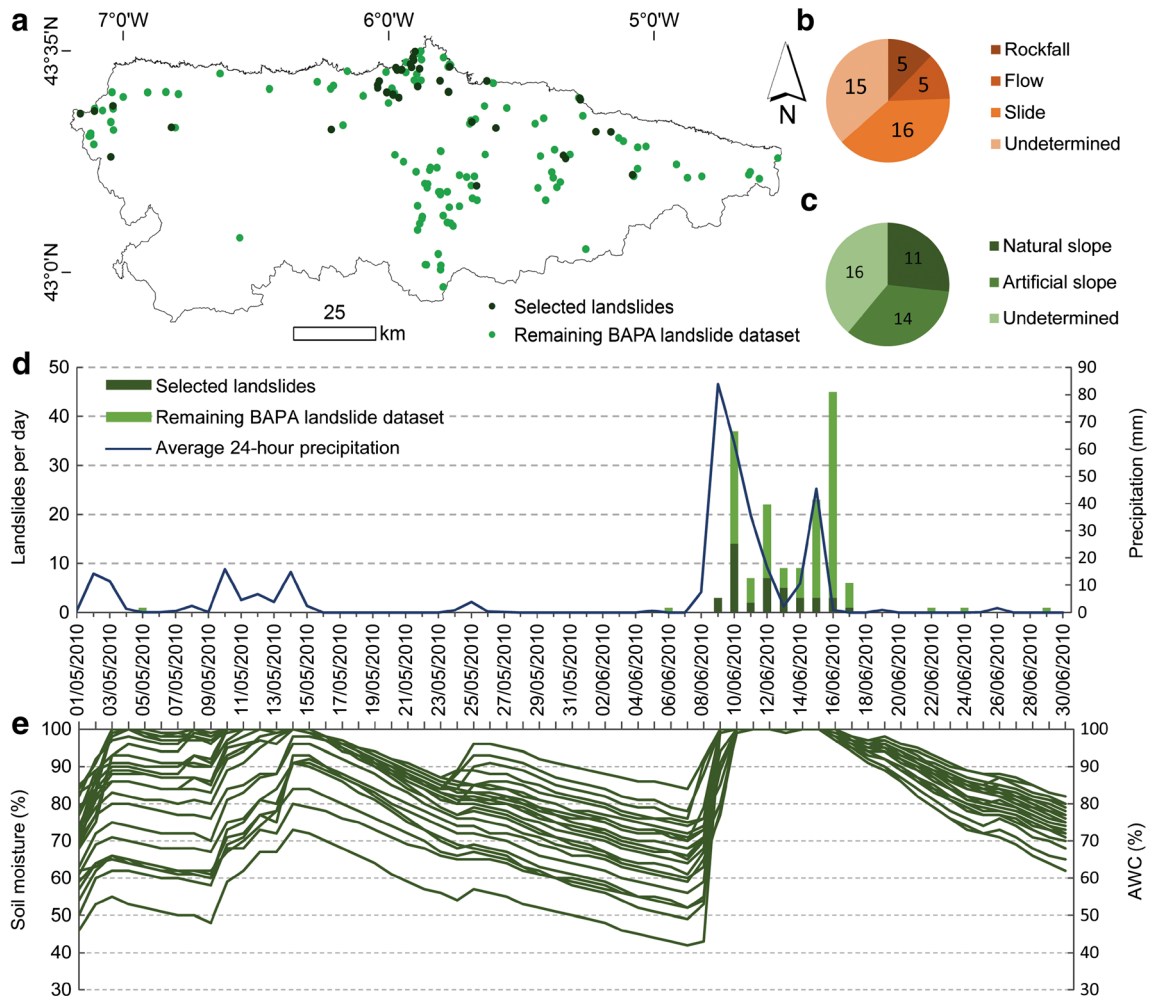


Fig. 3 A spatial location of the landslides from the BAPA database recorded for the 2010 period, differentiating those ones selected for the analysis; **b** type of landslide; **c** type of slope; **d** temporal distribution of the landslide records (differentiating those ones selected for the analysis) for the 2010 period and its relation to average 24-h precipitation values for the location of the selected landslides (extracted from AEMET water balance models; Botey and Moreno 2012); **e** evolution of the soil moisture conditions, expressed in percentage of AWC, for each selected landslide location during the 2010 period

In both cases of study, the occurrence of landslides was coeval with the periods with high levels of soil moisture (Figs. 2 and 3). The majority of the selected landslides took place in days with AWC levels of 100% (83.7% in the 2008 period and 92.7% in the 2010 period); the remaining ones took place in days with AWC levels of 99%, except two cases in the 2010 period, which occurred with AWC levels of 98%. Thus, AWC values of 99–100% were interpreted as critical soil moisture conditions for the landslide occurrence (Fig. 4).

The lapse with AWC levels between 99 and 100% in each selected location before the occurrence of the landslide ranged from 1 to 31 days in the 2008 period and from 1 to 8 days in the 2010 period. Accumulated precipitation values recorded during these periods were calculated and represented in a box-plot, considering data from (i) water balance model raster outputs and (ii) the nearest weather stations to the location of each landslide. Plotted dots represent values considered as outliers (Fig. 5).

For the 2008 period, the difference in the distribution of the accumulated precipitation values from raster outputs and weather

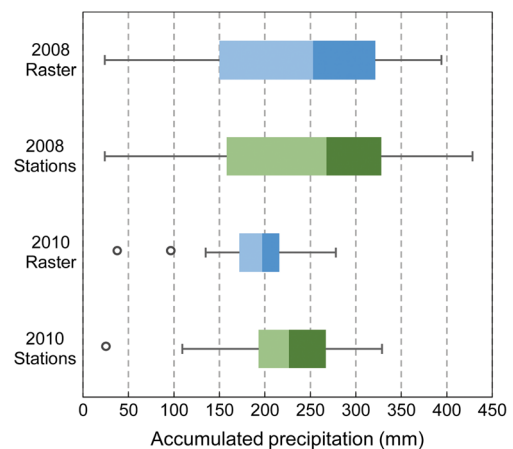


Fig. 4 Distribution of the accumulated precipitation values recorded during the period with high soil moisture conditions (AWC 99–100%) before each landslide. Data come from water balance model raster outputs (blue) and weather stations (green). Plotted circles represent values considered as outliers

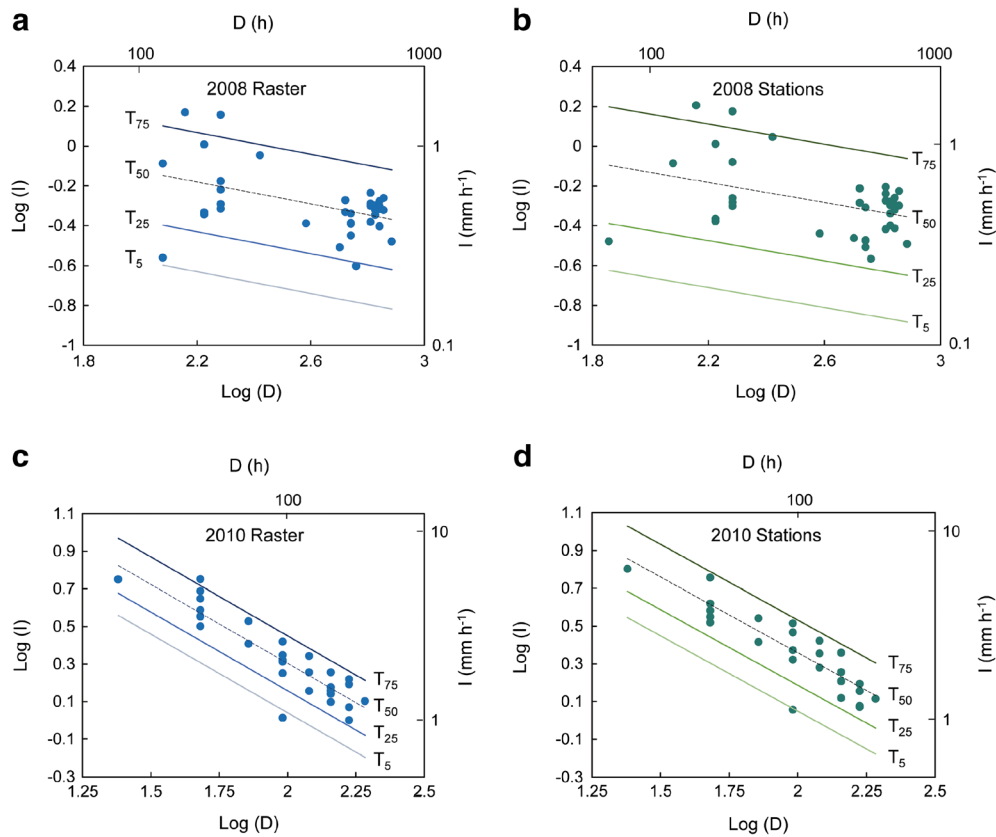


Fig. 5 I - D rainfall-thresholds for the landslides triggering for the 2008 period (a and b) and the 2010 period (c and d). Thresholds corresponding to the 5, 25, 50, and 75% exceedance probability calculated based on data from raster water balance models (a and c) and nearest weather stations (b and d)

stations is not very important; both sets of data show a big dispersion. For the 2010 period, the dispersion is lower than in the previous case but the distribution of both sets of data shows significant differences, reaching highest values in the case of the weather stations. Based on these data sets, I - D thresholds for different probabilities of occurrence were calculated for both cases of study (Fig. 5). Moreover, the corresponding equations were included in Table 1.

Discussion

Observed correlation between the days with a high number of landslide records and the days with high values of average 24-h precipitation in both study periods confirmed the relevant role of precipitation as the main trigger of landslides within the study area, previously pointed out by Dominguez-Cuesta et al. (1999, 2012). In some cases, the day with the highest number of landslides occurred after the maximum daily precipitation value (e.g. November 25, 2008, or June 16, 2010) (Fig. 2d and Fig. 3d). Considering this fact, accumulated rainfall could have more influence than rainfall intensity in landslide triggering; however, almost 72% of the landslides recorded during these days shows low temporal accuracy levels, which hamper the possibility of reaching any conclusion in this aspect. Moreover, no landslides were reported in some days with significant precipitation values, such as the October 21, 2008, and the October 27, 2008 (Fig. 2d) or the period between May 10, 2010, and May 15, 2010 (Fig. 3d). A possible

explanation for this fact could be the incompleteness of the landslide database for those periods. However, the significant concentration of landslides in periods with high levels of soil moisture, observed in both cases of study, suggested a close relationship between both parameters.

When a rainfall episode takes place over an area with low levels of soil moisture, precipitation contributes to raising the water table and, consequently, increasing the pore water pressure, but no landslides are triggered; this fact may be observed during the periods October 27, 2008–November 1, 2008 (Fig. 2) and June 8, 2010–June 9, 2010 (Fig. 3). Only when critical soil moisture conditions (AWC of 99–100%) are reached, precipitation events trigger landslides. This behaviour may be observed on November 2, 2008, and on June 10, 2010 (Fig. 2d–e and Fig. 3d–e). Considering this, the defined critical soil moisture level could be considered a determinant conditioning factor for the landslide occurrence. Thus, precipitation that makes possible to reach that level plays a preparatory role. Only the rainfall accumulated after the moment that the AWC reaches 99–100% has been interpreted as triggering rainfall and considered in calculating the thresholds.

Although a rate of 99–100% of the AWC does not represent the complete saturation of the soil, the high amount of landslides recorded under those conditions suggests that the pore water pressure achieved is enough to trigger slope instabilities. These considerations agree with the results published by Posner and Georgakakos (2015), which show that most of the landslides analysed in their work take

Table 1 Equations of the thresholds from the 2008 and the 2010 episodes

	2008 raster	2008 stations	2010 raster	2010 stations
Threshold 5%	$I = 0.94 D^{-0.27}$	$I = 0.70 D^{-0.25}$	$I = 52.03 D^{-0.84}$	$I = 44.89 D^{-0.80}$
Threshold 25%	$I = 1.49 D^{-0.27}$	$I = 1.20 D^{-0.25}$	$I = 68.17 D^{-0.84}$	$I = 61.71 D^{-0.80}$
Threshold 50%	$I = 2.64 D^{-0.27}$	$I = 2.36 D^{-0.25}$	$I = 95.54 D^{-0.84}$	$I = 91.87 D^{-0.80}$
Threshold 75%	$I = 4.69 D^{-0.27}$	$I = 4.64 D^{-0.25}$	$I = 133.92 D^{-0.84}$	$I = 136.77 D^{-0.80}$

place under high soil water content but lower than the total saturation. Baum et al. (2005) and Godt et al. (2009) reached similar conclusions, proving the relationship between landslide triggering and times of high soil wetness (degree of saturation exceeds 60–80%). For these reasons, AWC index calculated considering Botey and Moreno (2012) can be regarded as a suitable criterion for the definition of the *I-D* parameters since the characteristics of the soil (soil type and texture, slope, depth of vegetation roots) are taken into consideration for its calculation. In addition, AWC raster outputs analysed at a daily scale show the spatial distribution of the zones in which these critical soil moisture conditions have been reached and, in consequence, the most prone areas for the triggering of landslides. Therefore, in these areas, the calculated thresholds could be implemented to forecast those phenomena.

An inverse relationship between average rainfall intensity (*I*) and duration (*D*) parameters was observed in all the calculated rainfall-thresholds (Figs. 5a–d). When previous soil moisture levels are low, high rainfall intensity values are needed to raise the critical AWC in a short time period and to trigger landslides. This fact is observable during the first days of the 2010 episode, when average precipitation values of 85 mm are needed to trigger slope instabilities (Figs. 3d and e). For this reason, the thresholds of the 2010 episode show higher intensity values for short durations (Figs. 5c and d). However, after a long precipitation period, lower intensity values could trigger a landslide. This can be observed on the days November 12, 2008, and November 13, 2008, when the recorded instabilities were triggered by an average precipitation lower than 10 mm (Figs. 2d and e). This is consistent with the low intensity and long duration conditions defined by the thresholds of the 2008 period (Figs. 5a and b).

The thresholds calculated from weather station data are slightly higher than those calculated from water balance models. This fact could be explained by the kriging interpolation method used during the modelling, which makes all the interpolated values lower than the empirical input data. The smoothing effect may be more intense in the cases of short-duration isolated and heavy rainfall events, without precipitation during the previous and subsequent periods. This is the case of the 2010 period, where accumulated precipitation values from weather stations are higher than those extracted from water balance models for the same period (Fig. 4). However, this fact is not significant for the typical long humid periods in Asturias (2008 period), when the oscillation in daily rainfall values is not so important and the precipitation is generalised over the study area. Thus, weather stations close to the place of occurrence of the landslides may provide more accurate precipitation records. In any case, the use of data from water balance models implies an advantage in those areas with low density of weather stations or when precipitation records show significant data gaps.

Figure 6 shows a comparison between the *I-D* thresholds defined for both studied episodes and six different *I-D* thresholds previously defined by Corominas et al. (2005) and San Millán Revuelta (2015) for the North of the Iberian Peninsula and Caine (1980) and Guzzetti et al. (2008) for the world. Five percent probability of exceedance thresholds calculated from weather stations data for the 2010, and the 2008 periods are interpreted as the minimum thresholds for the occurrence of landslides in the Asturian region. Despite the difference in scale, both thresholds are located within the range of conditions defined by the global thresholds set by Caine (1980) ($I = 14.82 D^{-0.39}$) and Guzzetti et al. (2008) ($I = 2.2 D^{-0.44}$). The minimum threshold calculated for the 2010 period in Asturias ($I = 44.89 D^{-0.80}$), characterised by short duration and intense rainfall, could be comparable to the more restrictive threshold III defined by San Millán Revuelta (2015) for Cantabria (N Spain) ($27.11 D^{-0.62}$). Moreover, the *I-D* threshold ($I = 17.96 D^{-0.59}$) defined by Corominas et al. (2005) for the Eastern Pyrenees area (Spain) is consistent with the minimum threshold for the 2010 period, although the first one has been defined for moderate intense rainfall episodes (Fig. 6). By contrast, the analysis of the 2008 period allowed the definition of a very low minimum threshold ($I = 0.70 D^{-0.25}$), consistent with the typical rainfall pattern (low-intensity and long-duration events) of the wet period in Asturias. A comparison could be made with the two approaches of minimum thresholds I and II ($I = 0.48 D^{-0.54}$; $I = 9.33 D^{-1.13}$) published by San Millán Revuelta (2015) for Cantabria (N Spain), showing the most restrictive performance of the thresholds calculated for the 2008 period. In all the cases, observed differences could be related not only to the climatic differences between the areas but also to the limited number of landslide events used to define the thresholds, which could exacerbate the particular conditions of the analysed cases.

The methodology used in this work presents some restrictions to be considered. Firstly, different types of landslide have been considered jointly for the present analysis; this fact might be seen as a limitation of the study since the level of influence of rainfall as a trigger is different depending on the affected substratum or the natural or human origin of the involved slope. Moreover, analysed landslide events derived only from two rainfall episodes. Secondly, precipitation distribution shows a great spatial variability in Asturias, taking into account its extent and landscape variability, so that average rainfall values for the entire study area must be seen as estimations. Finally, precipitation intensity and duration patterns observed during the two selected periods are the results of the specific atmospheric synoptic conditions observed in these particular cases. However, it could be expected that other different atmospheric synoptic conditions may also give as a result of precipitation events with similar characteristics. Consequently, new studies over a higher number of cases are needed to

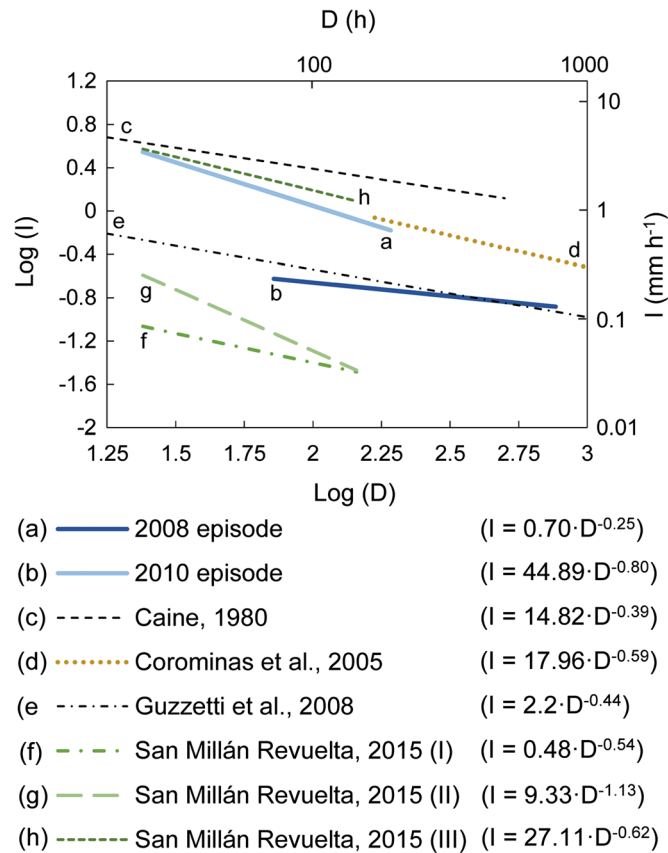


Fig. 6 Comparison between minimum I - D rainfall thresholds corresponding to the 2008 and the 2010 episodes and other I - D thresholds defined for the world by Caine (1980) and Guzzetti et al. (2008), and for the N of Spain by Corominas et al. (2005), and San Millán Revuelta (2015)

determine the frequency of the different synoptic patterns that trigger landslides.

The present work establishes for the first time the minimum conditions of soil moisture and precipitation for the occurrence of slope instabilities at a regional scale in a representative area of Northern Iberia, giving valuable criteria to define general early warnings related to landslide triggering in this region.

Conclusions

Available water capacity (AWC) is a convenient hydrogeological index to represent the soil moisture evolution and its role as a conditioning factor for the triggering of slope instabilities related to rainfall events. Almost 98% of the landslides recorded during both study periods (October–November 2008 and June 2010) took place under AWC levels of 99–100%, interpreted as critical conditions for the occurrence of landslides. Daily water balance model raster outputs may be used to determine the periods and areas in which these conditioning soil moisture levels are reached and, consequently, to establish when and where the calculated rainfall thresholds may be implemented. Thanks to the I - D thresholds, minimum probabilities of landslide occurrence have been estimated for the main precipitation patterns identified in the study area. Although the designed methodology shows some geomorphological and climatic limitations, rainfall thresholds based on soil moisture parameters are calculated for the first time in Northern Iberia, giving an accurate

approach for the establishment of precipitation as landslide triggering in this region.

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