Rainfall and weather conditions inducing intense landslide activity in northern Spain (Deba, Guipúzcoa)

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Abstract. The Deba area is intensely affected by frequent shallow landslides triggered by rainfall. This contribution explores the role of rainfall in landslide activity during a quite long time span (60 years), from a large network of rainfall gauges and a complete inventory of landslides. Out of 1,180 landslides inventoried, more than 50% occurred simultaneously in 6 known dates, corresponding to 6 episodes triggering multiple landslides; 3,241 rainfall episodes have been automatically recognized and characterized in terms of rainfall amount and duration, providing a representative dataset that covers a wide range of movement types and behaviors.

Relationship between rainfall episodes driving multiple movements simultaneously has not been explored in depth so far in northern Spain. The analysis provides different results. The extraordinary character of the triggering rainfall has been assessed and empirical rainfall thresholds (total amount, and mean intensity), producing multiple landslides, has been found and compared with others described in literature. Also, the meteorological conditions associated to those extreme events have been recognized: multiple landslide occurrences are triggered by extreme convective rainfall: intense, short and with limited horizontal extent, as well as a marked summer-autumn seasonality. This weather pattern is more characteristic of Mediterranean areas than of mild marine west-coast climates.

The definition of the conditions of the multiple landslide occurrence events, qualitative and quantitative, makes it possible to better understand the behaviour of slopes, which is essential for better predictability of landslide occurrence.

Key words: shallow landslides, multiple landslide occurrences, rainfall thresholds, landslide-triggering meteorological conditions

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1 Introduction

Landslide hazard assessment must be based on a detailed knowledge of the triggering factors: snow melting, river or marine basal erosion, seismic activity, rainfall or human intervention. However, rainfall-induced landslides are the most widespread phenomena, especially in mountain areas. In this type of movements, the occurrence depends on the response to water of the terrain materials (Corominas and Moya, 1999; Crozier, 1999; Corominas, 2001; Peruccacci et al., 2012, 2017). The role of rainfall acquires special relevance in extraordinary episodes capable of producing numerous landslides simultaneously (Crozier, 2005).

There is a large number of references in the literature aimed at finding relationships between rainfall and landslides, especially regarding the determination of a critical rainfall threshold. That is, a minimum value of rainfall (although the soil moisture or hydrological conditions can be also taken into consideration) beyond which landslides have occurred in the past, and therefore are likely to do in the future (Reichenbach et al., 1998; Crozier, 1999; Aleotti, 2004; Martelloni et al., 2012; Palladino et al., 2018).

The methods based on empirical observations are focused on the statistical analysis of the relationship between rainfall and landslides. That is, on the identification and characterisation of specific rainfall episodes that, due to their exceptional character, have led to produce landslides. These methods provide thresholds based on different rainfall parameters: total volume, intensity, duration, or combinations of them, such as the typical intensity-duration (I-D) threshold, widely used for shallow landslides. Global thresholds were proposed initially by Caine (1980) from worldwide landslide occurrences. More recently, a broad list of thresholds, obtained from a review of the literature, is provided by Guzzetti et al. (2007, 2008). Segoni et al. (2018) analyse the main drawbacks of the rainfall thresholds published worldwide in the last decade. They highlight that: a) only few works deal with long and complete datasets, b) the exact moment of the occurrence is frequently uncertain, and c) rainfall data often derives from a scarce rain gauge network density and limited to daily data.

Although many of these restrictions are normally unavoidable, in the municipality of Deba (Guipúzcoa, northern Spain), there is an unusually long and complete landslide inventory for the recent past (1953-2015). Landslide record represents an entire spatial coverture of the movements occurred in the study area (about 50 km^2) for the period analysed. It has been possible to identify 6 dates in which multiple landslide occurred; they represent more than 50% of the movements recorded over the whole period. Also, a good number of rain gauge stations, with appropriate length and high quality, is available. Furthermore, there are several reports with meteorological descriptions of the episodes responsible for the 6 identified events, precisely due to the relevance of their consequences.

In consequence, this long and complete spatio-temporal record of movements and precipitation data, although with limitations, provides a great opportunity to carry out an assessment of the characteristics of the rainfall capable of producing intense landslide activity in this area.

In fact, in the Cantabrian Range, where landslides are a common and widespread geomorphic process, only a few works related to landslide-triggering rainfall pattern have been carried out both in the study area (Bonachea et al., 2016; Rivas et al., 2016; Remondo et al., 2017) and in nearby regions (San Millán, 2015, 2016; Valenzuela et al., 2017a, 2018, 2019; Bornaetxea et al., 2018).

In this context, the main objective of this work is to determine the rainfall conditions that are likely to produce slope movements in the area, specifically on extraordinary episodes producing multiple shallow landslides (numerous and simultaneous movements). The reconstruction of the past landslide occurrence entails the identification of the major rainfall episodes that have caused multiple landslides, as well as the estimation of the exceptional magnitude of them through a set of three indicators (cumulative, antecedent and mean rainfall intensity). In order to improve hazard assessment, site-specific thresholds are obtained and compared with others from similar geomorphic and environmental settings. Also, a tentative conventional I-D function is presented; despite of data limitations and uncertainties, it is useful, with caution, for comparison purposes. Furthermore, the meteorological conditions associated to these extreme rainfall episodes are investigated and a weather pattern (type and seasonality) linked to multiple landslide occurrence is identified. Altogether, the results found reproduce empirically the rain critical values and the weather conditions associated to the six most outstanding events of multiple landslide occurrences in the area for the observation period, which are the more dangerous as well.

2 Study area

This work has been carried out in the municipality of Deba, in north-western Guipúzcoa (Basque Country, N Spain) (Fig. 1), with an extension of about 50 km^2. The relief is strong, with heights between 0 and almost 900 m a.m.s.l. and average slope gradient of 27º. There are narrow valleys, delimited by rectilinear slopes, and a coastline characterised by steep cliffs. Vegetation cover is quite continuous and consists mainly of cultivated prairies and pine trees. Climate is mild and humid, and corresponds to temperate oceanic type of

Köppen classification (Cfb). Annual rainfall is around 1,500 mm, with low interannual variability. The monthly rainfall distribution displays an unmarked seasonal cycle, without summer drought. The maximum values occur in winter and autumn linked to frontal disturbances; during summer, the Azores anticyclone produces drier conditions, although episodes of intense rain are relatively frequent in this season. Lithology is constituted by sedimentary bedrock of flysch facies, lutite, marl and limestone, with a mantle of well-developed heterogeneous surficial formations on which landslides develop. This regolith consists of unconsolidated weathered and colluvial materials, with thickness ranging in general between 0.5 and 3 m. Shallow landslides are widely distributed on slopes, affecting a significant extension of the study area. Rainfall increases pore water pressure and lowers the shearing resistance of the surface formations, resulting in instability.

3 Material and methods

The working team has been investigating for several decades in the study area, which can be considered a field laboratory, so that the methods and data used in this research are the result of an extensive history of collecting and processing information. The fact that rainfall is the main trigger of landslides in the area is well known. In this sense, many known precipitation episodes, which have caused landslides, have been recorded for the last 60 years; however, in most cases it has not been possible to identify all the landslides associated to them. Generally, either singular and well-dated landslides and for which rainfall amount can be estimated from nearby rain gauges have been identified, but they cover partially the occurrences in the study area, or all the landslides that have occurred in the area between two dates have been recognized, but the specific causal rain episode can not be discriminated. Only in six cases, all the occurred landslides produced by six precipitation episodes have been identified and mapped. As described below, it is precisely these 6 precipitation episodes, each causing numerous landslides, the key to understand the precipitation conditions that cause multiple simultaneous landslides.

3.1 Landslide inventory

Mass movements analysed in this study are shallow translational slides, of small size (≈500 m^2 and 200 m^3), affecting the regolith, being the most frequent type of movement in the area. Rupture surfaces develop at the contact between the regolith and the bedrock, usually parallel to the land surface and on average 1.2

m deep. Slides often turn into debris flows, particularly when regolith is thick or water presence is important (Remondo et al., 2003b).

The inventory of landslides covers a 60-year period and includes a total of 1,180 movements (Table 1) mapped using aerial photographs and orthophotos as cartographic base. Three situations of landslide activity can be recognized during the time spam analyzed (Table 1):

- Almost no activity periods: stages in which there have been only a few small landslides (< 4/year) or not movement at all.

- Undetermined landslide activity periods: phases in which shallow landslides have occurred, but the date of most of them is unknown and therefore cannot be attributed to any specific rainfall triggering episode. In the periods 1954-1970, 1970-1983 and 1993-1997 many landslides have occurred (109, 104 and 223, respectively) but, since the date is unknown, it is not possible to link them with any of the numerous rainfall episodes happened in those periods. Also, the high number of landslides during those periods does not necessarily mean that they occurred simultaneously; they could have been temporarily distributed throughout the entire period. In fact, the dates of occurrence of a few individual landslides are known but their spatial distribution is not random neither in the space nor in time (they are spatially related to their accessibility and temporally linked to damaged elements). It is important to highlight that the landslides analyzed in this work are exclusively those occurred on natural slopes and not on road slopes whose stability is highly conditioned by constructive works (material properties weakening, drastic change in slope gradient, natural water flow disruption, etc.).

- Periods characterized by known events of multiple occurrence of landslides: phases in which abundant landslides, distributed throughout the study area, have occurred simultaneously as a consequence of a specific and known rainfall episode. These events with abundant landslides might be classified as MORLE (Multiple-Occurrence Regional Landslide Events), as defined by Crozier (2005) for large areas. It is worth noting that the study area constitutes a small window of observation of a phenomenon extended over a wider area, and then with a regional relevance. Consequently, the number of landslides inventoried in each one of these periods is just a minimum sample of all those triggered by a unique episode of rainfall.

Six major landsliding events, which are responsible of 688 movements, more than 50 % of the total inventoried for the last 60 years, have been identified. Figure 2 shows the location of movements corresponding to the 6 rainfall episodes. Landslide amount differs from one event to another but tends to be concentrated in the north-eastern part of Deba because it is the most susceptible area (Remondo et al., 2003a, b).

The assignation of precise dates for these 6 events has been carried out on the basis of different information sources: post-event field surveys, technical reports of public agencies, aerial photographs, regional newspapers, research papers, applications for indemnities to insurance companies and personal communication of neighbours. More specifically, the landslides caused by the six precipitation episodes have been recorded in the following technical reports, research projects and scientific publications:

- October 1953: the identification of the landslides corresponding to this date is a consequence of a macro-project financed by the Provincial Council of Gipuzkoa. The torrential rains of August 1983 (next event identified in this work), which caused catastrophic floods and landslides throughout the region, highlighted the need for hazard studies, as well as detailed geomorphological and geological mapping. For this reason, a 1:5,000 mapping of past and present landslides was carried out. The 1953 rain episode caused disastrous consequences (economic losses and several deaths) in the Basque Country, and especially in Guipuzcoa, recorded in the National Catalogue of Historic Floods (Dirección General de Protección Civil y Emergencias). Specifically, the movements corresponding to the 1953 rainfall episode were easily identified from the recent-looking features observed in the January 1954 photos (the environmental conditions of the area make the instability features no longer visible because they disappear due to erosion or revegetation). The results obtained were presented in technical reports (DFG, 1986a, b; Tamés et al., 1986).

- August 1983: as mentioned above, the damages caused by the 1983 rainfall episode resulted in a macro study on natural hazards in the Basque Country. The investigations included field campaigns conducted immediately after the disaster, initially to estimate damage to process economic compensations, and immediately afterward, to produce the aforementioned 1:5,000 hazard maps (DFG, 1986a, b, 1991, 1999; Tamés et al., 1986; Cendrero et al., 1987).

- July 1988: landslides caused by this rainfall episode were used to validate the 1:5,000 landslide hazard maps. Again, intense fieldwork and data collection from press reports, neighbours surveys, etc. was carried out to identify the triggered landslides (DFG, 1991; Duque et al., 1990a, b; 1991; Salazar and Ortega, 1990).

- October 1992: again, landslides caused by this rainfall episode were used for evaluating the 1:5,000 landslide hazard maps previously elaborated but considering broader conditions; that is, instead of analysing the consequences of just a single rain event, to analyse two events (DFG, 1999; Remondo et al., 1996, 2000; Díaz de Terán et al., 1998). Field campaigns were also carried out after the rain episode. April 1993 photos were only used as cartographic base to better locate the identified landslides. Also, with this event began a PhD Thesis on susceptibility and landslide hazard modelling in Deba (Remondo, 2001). This inventory was also part of the European project “New technologies for landslide hazard assessment and management in Europe (NEWTECH)” (Corominas et al., 1998).

- August 2002: this landslide data set was developed through the field work linked to a PhD Thesis (Bonachea, 2006) within the framework of the European project “Assessment of landslide risk and mitigation in mountain areas (ALARM)” (Marcato et al., 2005). September 2002 ortophoto was used as cartographic base since the landslides were recent and easily identifiable (Remondo et al., 2003a, 2003b).

- November 2011: this landslide data set was elaborated from field campaigns after the storms event, within the framework of the Interreg European project "Développement d'Outils pour le Suivi des Mouvements de Sol pour la Gestion Durable de SUDOE (DO-SMS)" (Bonachea et al., 2012).

Unlike landslide catalogues that derive exclusively from press reports, which contain only landslides that produced damage on exposed elements, or were located in easily visible and accessible places, and therefore have a great bias, the inventory in this work may has some uncertainty in the exact number of movements (a minor bias), but it represents a complete spatial coverage of the landsliding behaviour.

3.2 Rainfall data and procedure

The rainfall data over the considered period (1953-2015) have been obtained from 15 meteorological stations (Fig. 1) with the most reliable records available, selected on the basis of length, completeness and quality. The rainfall data include 127,567 daily records; hourly ones are available only for a few stations and for recent times.

The selected stations provide a reasonable spatial representativeness of all the environmental conditions in the study area, but show a considerable data variability (up to 200 mm in a rainfall episode). This variability derives from the importance of local atmospheric conditions on intense rainfall. To solve this problem, the spatial distribution of rainfall was estimated with 22,614 daily rainfall spatial models (number of days within the period studied) obtained by interpolation from all gauges, applying the inverse distance weighting method (IDW, exponent 2 and a cell size of 100 m). Once these daily rainfall models obtained, the following strategies have been developed to characterize the rainfall events that have triggered the inventoried landslides:

a) Automatic determination of rainfall episodes for a central point, defined as the centroid of all the inventoried landslides (Fig. 2). Total daily rainfall data for this point was extracted from the daily spatial distribution models previously obtained. Subsequently, all the rainfall episodes were automatically computed. Each episode was individualized as a set of days with continuous rainfall higher than 0.1 mm. As a result, from 1953 to 2015, 3,241 rain episodes were automatically identified and characterized in terms of 1) duration; 2) average daily rainfall; 3) cumulative rainfall during the episode; 4) average daily rainfall intensity of the whole episode.

b) Accumulated rainfall for the central point. On the basis of total daily rainfall data at the central point, the amount of previous days was aggregated to each day, that is, accumulating the rainfall of the antecedent days. The number of days to be considered depends on the characteristics of the terrain and climate, which may vary widely depending on the local settings (Wieczorek, 1987; Crozier, 1999; Glade et al., 2000; Aleotti, 2004; Guzzetti et al., 2007; Li et al., 2011; Garcia-Urquía, 2016; Ma et al., 2016). For shallow landslides in slopes covered by permeable colluvium, where the interstitial pressure dissipates rapidly, the antecedent rainfall should not be so important, since the rainfall itself generates the hydrological conditions required for instability (Mateos et al., 2012). Also, the antecedent soil moisture conditions can be important for medium and long duration landslide trigger rainfall events (Zêzere et al., 2015). Particularly, in northern Spain, Valenzuela et al., (2019) found that more than a month of antecedent rainfall plays a significant role during the wet period, while the importance of antecedent rainfall is usually irrelevant for landslides triggered during dry periods. Still, trying to contemplate all the situations and since the antecedent rainfall is usually considered in this type of investigations, more than 6.33×10^5 records of accumulated rainfall were computed, from one single day up to periods of 28 continuous days, although according to our results 14 days period should be sufficient.

c) Characterization of rainfall episodes at each landslide location. From the 22,614 daily rainfall spatial distribution models obtained by interpolation, the daily rainfall was extracted at the precise points where known date landslides were triggered, 688 movements produced by the 6 major rainfall episodes. Thus, more than twenty thousand of rainfall daily data for each landslide were obtained (representing the number of days within the period studied at each landslide location). Since the evidences obtained from scientific and press reports post-event (see below, section 4.1) reveal that such rainfall episodes were much shorter in time and much greater in intensity than those obtained automatically, a selective data extraction has been carried out on the basis of those evidences. In fact, automatically computed rainfall episodes show, in general, a few days of intense rainfall, preceded or followed by insignificant amounts of rainfall. In this context, instead of considering the entire rainfall episode, only the period in which the movements were really triggered was used. In other words, the rainfall episodes have been adjusted to obtain values closer to reality, unattainable by automatic treatment. Then, rainfall episodes that triggered each landslide were extracted, resulting 688 pairs of data (rainfall amount and duration).

Then, a quantitative correlation between rainfall intensity and duration can be established, obtaining a tentative I-D threshold function. A power law curve is assumed: $I = \alpha D^{-\beta}$, where I is the rainfall mean intensity (mm/day) and D is the duration (day). In a logI vs. logD plot, α is the intercept and β defines the slope of the power function. From the best-fit function it is possible to establish parallel threshold lines for different prediction intervals of occurrence; the selected equation corresponds to an exceedance probability of 5%.

These proposed procedures represent identical treatments for all episodes of rainfall, providing representative data for each rainfall episode, in which the error will be equivalent in all cases. From these landslide and rainfall data, it has been possible to carry out a quantitative characterization of the 6 rainfall episodes driving multiple landslides (total rainfall, antecedent rainfall, intensity-duration thresholds) and typify their associated meteorological conditions.

4 Results and discussion

The instability in Deba area is characterised by an unequal distribution of landslides, both from the geographical point of view and the frequency of movements within the studied period. This variability is a consequence of a complex interaction among the different spatio-temporal patterns of the conditioning and triggering factors. The variability in total amount, duration and intensity of rainfall among the major 6 landsliding events is the principal cause of the difference in the number and density of landslides in each of them. However, in all 6 cases they have in common the extraordinary character of their rain values and meteorological circumstances, as shown below.

4.1 The 6 major landsliding events: meteorological conditions and seasonality

During the analysed time span, it has been possible to define six well-known multiple landslide events on the following dates: October 1953, August 1983, July 1988, October 1992, August 2002 and November 2011.

The rainfall of October 1953 had its origin in a perturbation of frontal character, although, unlike the habitual behaviour of this type of phenomena, it resembled more to a long-lasting convective storm, with very high intensity and moderate extension, similar to those usually produced by cold drops ("cut-off low") (DFG, 2006). Rainfall was mostly in a single day, reaching values much higher than 100 mm/24 hours and surpassing 200 mm/24 h in different parts of the region (Álvarez-Usabiaga, 1983).

The cold drop of August 1983 was qualified in those days as an extraordinary phenomenon with unprecedented values in the historical record, in terms of amount and intensity of rainfall, geographic extent, with a 500-year return period for the Basque Country. Although it lasted several days, data are conclusive determining that in just a few hours, the cumulative rainfall was more than half of a normal year (DFV, 1984; Pejenaute, 1991; Álvarez-Usabiaga, 1983; Capel, 1983; Fernández, 2004; Tamés et al., 1986).

The rainfall of July 18-19, 1988 was an episode also associated with a cold drop. The spatial distribution of rain was very irregular, with the Deba basin being one of the most affected areas. The total rainfall occurred in a period of 2 days, but practically 89 % fell in a single day. In fact, the description of this event in the National Catalogue of Historic Floods (http://www.proteccioncivil.es/cnih) mentions that "heavy rainfall started at 6:30 in the morning, but in only two hours 80 and 100 l/m^2 fell on the Deba and Urola river basins".

In October 1992, the presence of cold air in the upper level of the troposphere, low surface pressures and the arrival of a very cold and unstable polar maritime air mass created a very dynamic and persistent situation that turned into a high amount of rainfall (Pejenaute, 1996). In Eibar, the closest station with complete data, 330.5 mm fell between October 2nd and 12th, but 90 % had accumulated in the first 5 days. Lastur, a blind valley located in the municipality of Deba, reached 140 mm/24 hours (DFG, 2005).

Again, on August, 2002, the region was affected by a cold drop in which, in addition to intensity, duration was of utmost importance. The report of Euskalmet (Regional Meteorological Service) limits rainfall to the interval between days 24th and 28th (more than 180 mm of cumulative rainfall), with storms that persisted more than 6 hours, especially on the 26th.

The meteorological event that originated several landslides on November 2011 was due to the existence of a cold drop in the Mediterranean Sea that generated the arrival of a northern component air mass over the

Basque Country. The days 5^{th} and 6^{th} were responsible for most of the accumulated rain, exceeding 200 mm in Deba. The return period for this rainfall is close to 100 years (Euskalmet).

All extreme rainfall episodes described above have an evident association with the arrival of moist Atlantic airflows (sometimes topographically enhanced) combined with atmospheric upper level disturbances. Also, they show a common seasonal behaviour (summer and early autumn). This information provides evidences leading to a novel interpretation about the seasonality of the events of multiple landslide occurrences and the atmospheric conditions that generate them in northern Spain, which differ from the general idea maintained to the present.

According to Corominas (2006), failures in northern Spain are more frequent during winter and spring. In Cantabria, for a period of 10 years, San Millán (2015) observed that landslide frequency increases as of October, decreasing as the precipitation declines and evapotranspiration rises. In Vizcaya, a province bordering Deba, most of the landslides produced between 2002 and 2010, took place in autumn and winter (Díaz et al., 2012). In the same way, Valenzuela et al. (2017b), on the basis of data covering a 35-year period, found that in Asturias landslide distribution shows a positive correlation with monthly rainfall and the vast majority of landslides are linked to moderate-intensity frontal precipitation, occurring mostly from October to April. According to Valenzuela et al., (2018, 2019), convective precipitation is the principal trigger in dry periods (June-September) but generally produces a reduced number of landslides; although cut-off lows have been identified as a cause of landslides, the episode of June 2010, linked to hundreds of movements, is the only one recorded in the last 37 years.

In Deba, as in the rest of the north coastal area of Spain, most of the annual rainfall occur in winter, due to the action of Atlantic perturbations associated with Polar Front. These meteorological situations, generally produce long-lasting rainfall, sometimes even intense, and affect a large geographical area. However, exceptional values of maximum daily rainfall are usually associated with convective systems, favoured by meridian circulation, in some cases upper level stationary disturbances ("cut-off lows"), which cause thermodynamic instability. Although they may occur at any time of the year, they are more common in summer and autumn, and most of them manifest a local character (few hundreds of km^2) and vary substantially in intensity and duration within short distances (BOPV, 1999; DFG, 2005, 2006; Pejenaute, 2012).

It is thus clear that the long period covered in this study likely provides a representative picture of the meteorological conditions that trigger the multiple landslide events. Naturally, in Deba, other landslides, even multiple landslide events, do not comply with the weather pattern here described and were triggered, by long-lasting and low intensity rainfall episodes, typical of the wet season. However, the 6 events, which undoubtedly constitute the most significant ones (number of landslides associated with a single rainfall episode), present unambiguous signs of a certain Mediterranean-like behaviour.

4.2 Quantitative characterization of rainfall episodes driving multiple landslides

Once the nature of meteorological conditions associated to the 6 multiple occurrence of landslides established, it is appropriate to quantitatively determine the degree of exceptionality of those rainfall events. The rainfall amount and distribution of the 6 major rainfall episodes are illustrated in figure 2.

Based on the 3,241 rain episodes automatically computed, rainfall associated with the major landsliding events cover a quite large spectrum, in terms of total amount (63-280 mm). Figure 3a shows, for the central point, the total rainfall of the episodes without landslide activity (green dots) and the episodes that have triggered multiple landslides (red dots), as well as the curves representing the empirical percentiles, estimated over the entire 60-year period. Of the 6 major events, 5 have been associated with values of rainfall equal to or greater than 150 mm.

Previous studies in Asturias describe landslide initiation with 60 mm of cumulative rainfall, although several isolated slope instability events can even be triggered by lower rainfall values (Domínguez-Cuesta et al., 1999). On the other hand, the aforementioned landslide event of June 2010 in Asturias, equivalent to the ones described in the present work, was linked to 299.9 mm of precipitation in 9 rainy days (Valenzuela et al., 2018). For Guipúzcoa, Bornaetxea et al. (2018) estimated that episodes of 1-4 days that accumulate 60-120 mm of rain constitute the major cause of slope failures.

Although rainfall values around 150 mm seems not to be very high compared with those appearing in the literature for other geographic contexts (Guzzetti et al., 2007), it is actually extraordinary in the study area. This figure is only surpassed in 3 % of the episodes happened between 1953 and 2015, and from them, the majority corresponds to longer episodes (up to 36 days of continuous rainfall). As can be observed, rainfall episodes without landslides show a fairly lower amount for any duration of the episode. The 6 major landsliding events correspond with rainfall values above percentile 90, being 4 of them above percentile 99.9 (2011, 1983, 1953 and 1992) and one other above percentile 99.7 (1988). This analysis shows the extraordinary nature of the rainfall storms responsible for the multiple occurrence of landslides since, as a whole, with the sole exception of August 2002, they are among the 1 % of the rainiest episodes in the area for the last 60 years.

Concerning intensity, figure 3b represents I-D values of all rain episodes (automatically computed for the central point). Regardless of the duration, the intensity of the 6 well-known rainfall episodes associated with multiple landslides (15-35 mm/day) is among the highest of the 3,241 episodes and higher than those of no landslide activity. On the contrary, the rain episodes that coincide with periods of undetermined landslide activity (periods in which landslides have occurred, but the date is unknown and therefore cannot be attributed to any specific rainfall episode; Table 1) are in general lower. The results agree with the 33.3 mm/day of average intensity obtained for the June 2020 event in Asturias, responsible of hundreds of movements (Valenzuela et al., 2018).

In conclusion, although all of them are extreme, the multiple landslide events show important differences, both in the number of movements and in the amount and intensity of rainfall that triggered them; the 2002 event is clearly lower, since it was a quite long event of relatively low daily intensity, not exceeding 39 mm any day.

As an alternative procedure, and to validate the extraordinary nature of the rainfall values obtained, the antecedent rainfall was aggregated (Fig. 3c). Symbols in the figure match the 6 major landsliding events identified, accumulating rainfall up to the previous 13 days, 1-14, before landslide occurrence. Lines show empirical percentiles of rainfall. As can be seen, 3 of the 6 major events (1953, 1983 and 1992) constitute the most extreme events of the entire 60-year series, in 2 to 5 days of rainfall. The most extreme case corresponds to the 1983 episode, which represents the maximum rainfall accumulated in 2, 3, 4, 5 and 6 days of the period analysed. Other not so extreme events (1988 and 2002) also exceed 99 percentile (1988: 1 day of previous rainfall; 2002: 6-7 days of previous rainfall) for some duration. Thus, the rainfall responsible for more than 50 % of the landslides (688 from 1,180 landslides) in the municipality of Deba is within the 1 % of the most extreme rainfall episodes.

The three alternative analyses confirm again the extreme nature of the storms that have caused multiple landslides in the recent past.

4.3 I-D rainfall threshold

The resulting function corresponding to 95% confidence level is $I = 50.73D^{-0.428}$ (Fig. 4; inner graph). Therefore, any rainfall episode exceeding that threshold could be considered as a potential trigger of multiple slides. The I-D function is interpreted as the “minimum” rainfall threshold for the occurrence of multiple shallow landslides simultaneously and then it refers to extreme conditions. Of course, there may be other rainfall episodes (and probably have been) that produce similar landsliding effects but they are unidentified. In this sense, many of the landslides whose date of occurrence is unknown (undetermined activity) have probably occurred in similar extreme rain episodes.

The function obtained must be considered only as a rough estimate. Daily rainfall records led to underestimate the rainfall needed to trigger multiple landslides and will inevitably affect the accuracy of thresholds, although it is acceptable for defining regional thresholds.

With due caution, this I-D function makes it possible to determine the relative importance of intensity and duration in multiple landslide occurrences, as regards the climatic context of the study area and the type of slope movement. According to Guzzetti et al. (2008) in mild marine west-coast climate of mid-latitude region, rainfall duration is more important than intensity to initiate shallow slope failures, compared to areas of Mediterranean climate or even mountain areas where the intensity is more relevant. Secondly, shallow movements are usually related to short intense storms, while most deep-seated landslides are commonly triggered by rainfall periods lasting from several weeks to several months (Wieczorek, 1987; Corominas et al., 2002; Zezere and Rodrigues, 2002; Marques et al., 2008), or even by long-term variation of annual rainfall (Aleotti, 2004). Also, episodes of multiple and widespread landslides need longer durations than isolated ones (Guzetti et al., 2007, 2008). Thereby, multiple occurrence of landslides in Deba should be linked to intense mid-term rainfall. Intense rain is necessary for the triggering of shallow landslides affecting the regolith that is very sensitive to pore water pressure variations, and middle duration is determinant for the multiple occurrence. The obtained rainfall I-D function (-0.4 exponent) is coherent with that statement.

In figure 4, intensity and duration functions described in literature (similar environmental conditions) have been converted into daily units to better compare with the one here obtained. The results presented by Guzzetti et al. (2007, 2008), from tens of rainfall thresholds worldwide, suggest that those local are usually slightly higher than regional, and higher than global ones, due to an effect of the spatial scale. As a result, in equal conditions, it would be reasonable for our threshold to be higher than others of the ensemble (Fig. 4). The threshold obtained in this work, with a very local character, is higher than the global-regional ones associated with shallow landslides, provided by Guzzetti et al. (2008), for episodes above and below 48 hours, respectively. It is also worth comparing the threshold obtained with closer examples, of a local or regional origin, such as the figures published for the Pyrenees and Asturias, in northern Spain (Fig. 4).

For the Eastern Pyrenees, Corominas et al. (2005) established a regional I-D threshold to initiate mass movements in low permeability clays, applicable to events of rainfall longer than 165 hours. The threshold reported is comparatively high, but it must be considered that it refers not only to shallow landslides and that there are significant differences with the study area of this work, in terms of lithology (mainly, the type of regolith), land use and climate. It is then straightforward that the conditions that control their triggering are not comparable.
On the contrary, Asturias does correspond to the same climate, although with some differences in the type of movement, environmental conditions (geomorphological and geological) and time periods covered, which could justify the found discrepancies. Valenzuela et al. (2017a), estimated regional minimum thresholds from 2 major landsliding events occurred in 2008 and 2010. One threshold corresponds to an episode of low-intensity and long-duration event; the other is related to a short duration and intense rainfall. While in Asturias the threshold is obtained jointly for all types of landslides, shallow and deep, including those produced in road slopes, the threshold in Deba only represents shallow landslides affecting only the regolith in natural slopes. However, the latter function is not very different to the one for Deba. It is not obvious to explain the reasons for the differences but in any case, the Asturian function corresponds to a single precipitation episode (June 2010), while the one from Deba represents 6 major landsliding events with variable rainfall intensities, some of which, like the one in 2002, may produce a downward skew.
In Cantabria, a region also located in northern Spain and even closer to the study area, relationships between rainfall and landslides associated to roads, for a period of 10 years, have been characterised by San Millán et al. (2016). Authors provide several rainfall thresholds corresponding to different types of landslides; the most representative is clearly lower than the one obtained in this study for Deba. This fact can be explained because only man-made slope-cuts failures have been contemplated, much more prone to sliding and, therefore, much lower precipitation thresholds are needed to produce failures.

Overall, it is necessary to remark that this work has identified and characterized in detail 6 extraordinary rainfall-landslide events responsible of around 50% of the landslides identified within a period of 60 years, a wider and more representative time span, while the periods studied in other areas are much more limited. Again, the threshold here obtained does not refer to the minimum I-D rainfall conditions required to initiate a landslide but the rainfall capable of producing multiple landslide occurrences. Likewise, in Deba, other landslides occur under less extreme rainfall conditions but this work allow to understand the singularity of this kind of events, not very frequent but of great relevance for the instability dynamic in the study area.

In order to improve the thresholds here obtained, especially for warning system purposes, it would be advisable to apply validation approaches, that allow to assess the level of uncertainty of the prediction and forecasts (Guzzetti et al., 2008; Chang and Chiang, 2009; Brunetti et al., 2010; Berti, 2012; Peruccacci et al., 2012; Melillo et al., 2016). An updated database, with a greater number of new events, or independent databases for close areas, would be very useful to test the results obtained in Deba.

5 Conclusions

Landslides occurrence in Deba (NW of Guipúzcoa, Spain) during the last 60 years have been analysed concerning their main causal agent: extreme rainfall. The study refers exclusively to shallow landslides, the most frequent in the region.

Six major rainfall episodes causing multiple landslide occurrence (around 50 % of the 1,180 slope movements inventoried), have been identified and analysed in depth. The importance of this kind of multiple landslide events has not been previously recognised, during a so long period, in the north of Spain. The results obtained allow to understand the singularity of a relevant landslide-triggering rainfall pattern, across a representative period.

Rainfall and weather conditions responsible of intense landslide activity have been characterised and quantified, applying different strategies. The quantitative analysis of the rainfall episodes driving multiple landslides shows that they are extraordinary in both quantity and intensity. An I-D threshold function has been obtained, which represents a “minimum” rainfall value necessary for generating multiple landslides simultaneously. This local function has been compared with other described in close areas, despite the differences on the type of process, terrain and climate.

The meteorological conditions associated to these events have revealed a clear relationship with stormy phenomena (convective origin), characterized by rainy spells of especially high intensity, short duration, for the climatic context of the area, and relatively local dimension. This type of situation is especially frequent in summer and early autumn seasons, showing a behaviour more characteristic of the Mediterranean area.

In spite of the existing uncertainties and the subsequent limitations of the results, the better knowledge of the influence of rainfall in the study area will be useful to improve landslide hazard assessments. In this way, these results constitute a significant improvement in the geomorphological knowledge about the landslide process in the study area and the rainfall triggering conditions, all of which can be very useful to make hazard predictions.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Table 1. Periods of landslide activity. Characteristics of the images used for the temporal inventory of landslides.

Cartographic base			No. landslides identified	Landslide activity
Flight date	**Scale/ Resolution**	**Colour/BW**		
21/June-30/June, 2015	25 cm	Colour	3	Almost no activity
16/July-03/October, 2014	25 cm	Colour	3	Almost no activity
30/July-04/September, 2013	25 cm	Colour	8	Undetermined date
23/July-08/August, 2012	25 cm	Colour	18	Multiple landslides (November 2011)
19/June-25/June, 2011	25 cm	Colour	1	Almost no activity
04/June-01/July, 2010	25 cm	Colour	9	Undetermined date
23/April-29/May, 2009	25 cm	Colour	5	Undetermined date
27/July-06/October, 2008	25 cm	Colour	6	Undetermined date
17/March-06/September, 2007	50 cm	Colour	0	Almost no activity
17/July-14/November, 2006	25 cm	Colour	9	Undetermined date
02/June/-15/July, 2005	50 cm	Colour	0	Almost no activity
15/July-28/September, 2004	25 cm	Colour	4	Almost no activity
10/September-29/September, 2002	25 cm	Colour	23	Multiple landslides (August 2002)
1/September-30/September, 2001	1 m	Colour	8	Almost no activity
3-4 April, 1997	1/18000	Colour	223	Undetermined date
April-August, 1993	1/15000	Colour	95	Multiple landslides (October 1992)
March, 1991	1/18000	Colour	133	Multiple landslides (July 1988)
June-September, 1985	1/15000	BW	141	Multiple landslides (August 1983)
May-June, 1983	1/18000	BW	104	Undetermined date
No Data, 1970	1/15000	BW	109	Undetermined date
January, 1954	1/12000	BW	278	Multiple landslides (October 1953)

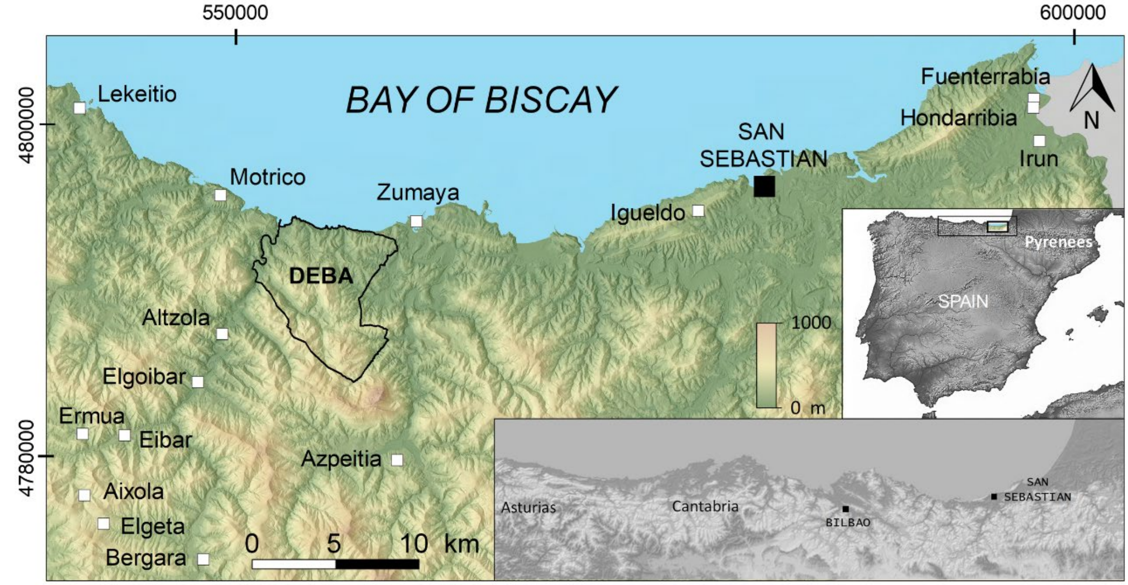

Figure 1. Study area location (Deba), weather stations (white squares) and places mentioned in the text.

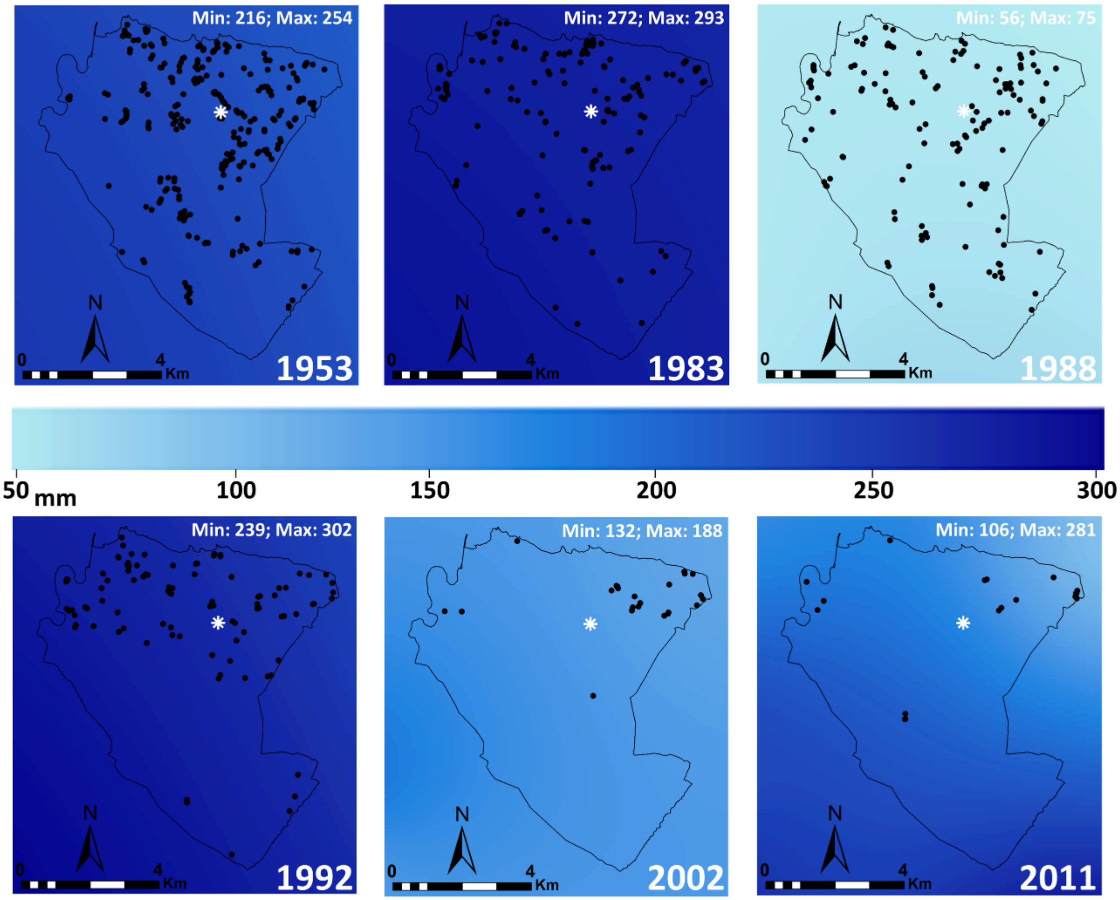

Figure 2. Rainfall patterns of the 6 major rainfall episodes responsible of causing multiple landslides. Landslides produced by each episode are also represented (black dots); Total amount of rainfall (mm) associated to each movement is shown. The white asterisk is the central point that corresponds to the location for which rainfall has been automatically estimated.

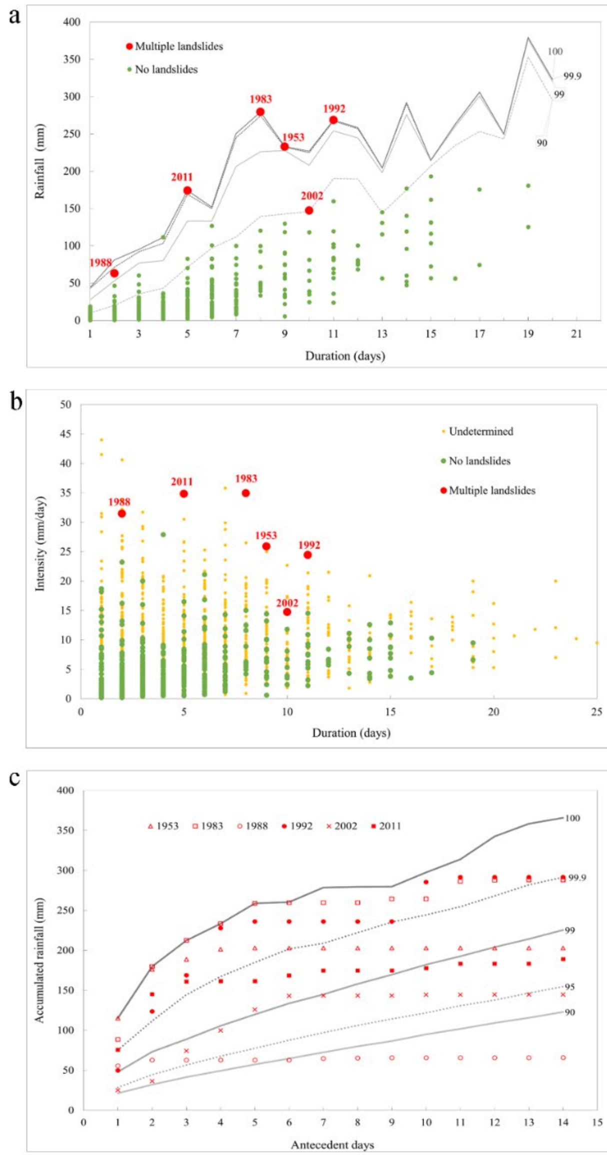

Figure 3. Quantitative characterization of rainfall episodes with multiple landslides. a: Rainfall amount and duration of the episodes automatically defined (only multiple landslide occurrence events, red, and no-landslide activity periods, green, are presented). Lines correspond to empirical percentiles, based on the 3,241 rainfall episodes. b: I-D values for all the 3,241 rainfall episodes occurred from 1953 to 2015 for a central and representative point in the area. c: Aggregation of 1-13 daily antecedent rainfall empirical percentiles. Symbols correspond to the 6 major landsliding events.

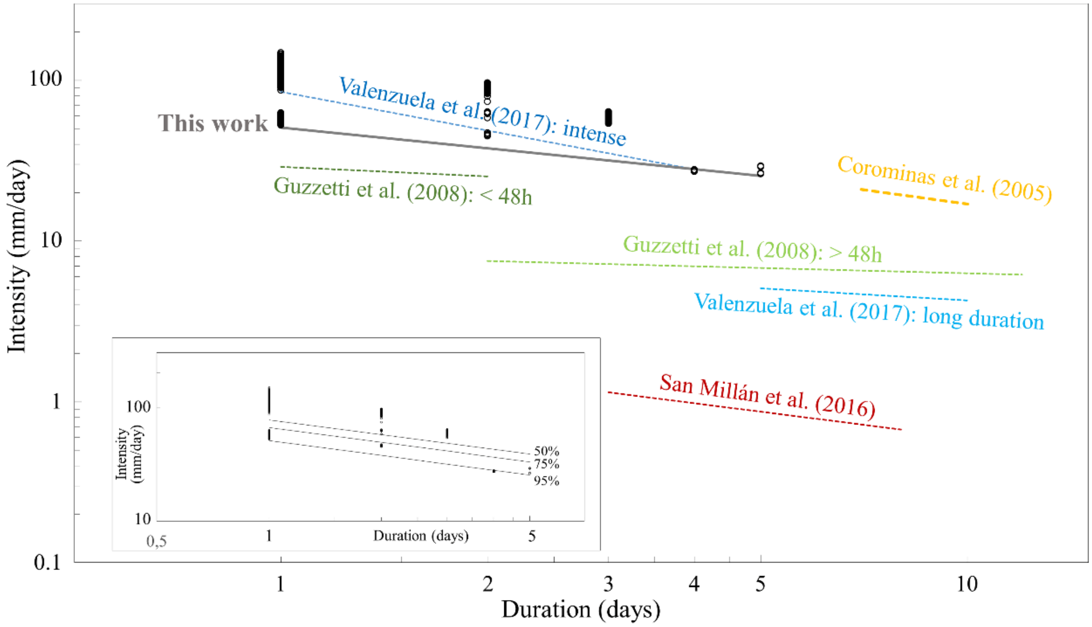

Figure 4. I-D rainfall function obtained in this work and comparison with thresholds of other authors referenced in the text. Hollow circles represent I-D values for the 688 dated landslides (black dots are result of the overlapping). The inner graph shows I-D thresholds (mm/day) for different prediction intervals.

Figure captions

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