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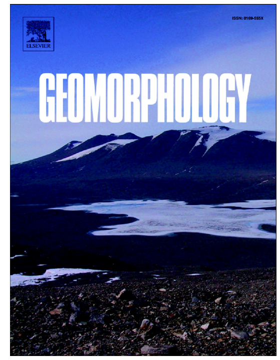

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PII: S0169-555X(17)30213-1
DOI: doi: 10.1016/j.geomorph.2017.05.010
Reference: GEOMOR 6037

To appear in: *Geomorphology*

Received date: 8 March 2016
Revised date: 10 May 2017
Accepted date: 16 May 2017

A spatio-temporal landslide inventory for the NW of Spain: BAPA database

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Abstract

A landslide database has been created for the Principality of Asturias, NW Spain: the BAPA (Base de datos de *Argayos* del Principado de Asturias – Principality of Asturias Landslide Database). Data collection is mainly performed through searching local newspaper archives. Moreover, a BAPA App and a BAPA website (http://geol.uniovi.es/BAPA) have been developed to obtain additional information from citizens and institutions. Presently, the dataset covers the period 1980–2015, recording 2063 individual landslides. The use of free cartographic servers, such as Google Maps, Google Street View and Iberpix (Government of Spain), combined with the spatial descriptions and pictures contained in the press news, makes it possible to assess different levels of spatial accuracy. In the database, 59% of the records show an exact spatial location, and 51% of the records provided accurate dates, showing the usefulness of press archives as temporal records. Thus, 32% of the landslides show the

highest spatial and temporal accuracy levels. The database also gathers information about the type and characteristics of the landslides, the triggering factors and the damage and costs caused. Field work was conducted to validate the methodology used in assessing the spatial location, temporal occurrence and characteristics of the landslides.

Keywords: Landslide database, Press archives, Rainfall, Asturias.

1. Introduction

Landslides are local phenomena, usually linked to more conspicuous hazards, like intense rainfall, floods or earthquakes. For this reason, they have often been undervalued (Foster et al., 2012). However, landsliding is one of the most frequent and widespread natural hazards worldwide, causing considerable human and material losses each year (Petley, 2012; Papathoma-Köhle et al., 2015). Major efforts have been made to study the characteristics of landslides and assess their impact (Damm and Klose, 2015) and for these purposes, a landslide database is of primary importance (Guzzetti et al., 2012; Van Den Eeckhaut and Hervás, 2012).

Landslide databases, or digital landslide inventories, constitute a detailed registration of the distribution and characteristics of past landslides (Hervás, 2013). Although the contents and completeness of databases vary depending on their function (Damm and Klose, 2015), the stored dataset usually contains: (i) core attributes (ID number, location, occurrence date, and movement type), (ii) additional information (geometry, controlling and triggering factors, impacts, mitigation measures and costs) and (iii) complementary data (illustrations, aerial photos and monitoring data) (Hervás, 2013). Thanks to geographical information systems (GIS), it is common to represent the spatial distribution of landslides using landslide inventory maps (Guzzetti et al., 2012).

Depending on the information source used, these databases can be classified into two main categories (Guzzetti et al., 2000; Malamud et al., 2004; García-Urquia, 2014): (a) archive inventories, containing information obtained from archive sources (press, scientific literature, historical archives and previous inventories), and (b) geomorphological inventories, containing information obtained from geomorphological field work, aerial photo and satellite imagery interpretation or analysis of digital elevation models (DEMs). The first group usually offers better temporal information than the second, which provides more detailed data about genesis and geometry. In this way, archive inventories are essential in the temporal forecasting of landslides, while spatial information provided by geomorphological inventories is required for a spatial assessment of linked susceptibility, hazard or risk. In many cases, both types of sources are used to create a landslide database (Guzzetti et al., 2012). New technologies also constitute a rich source of information about landslides and other natural hazards through the use of free cartographic servers such as Google Earth (Van Den Eeckhaut et al., 2012), on-line report systems (Baum et al., 2014), web data mining (Battistini et al., 2013) and social media such as Twitter (Pennington et al., 2015).

The aim of this paper is to present a new landslide database developed for the Asturian region (NW Spain): the BAPA (Base de datos de *Argayos* del Principado de Asturias – Principality of Asturias Landslide Database). This database records data for the period 1980–2015 based on press archives and reports from citizens and institutions. The main goals of this paper are to: (i) describe in detail the methodology used for developing the BAPA, (ii) present the compiled information, (iii) discuss data accuracy, and (iv) analyse the spatial and temporal distribution of the dataset in relation to landslide conditioning and triggering factors for Asturias.

2. Background

There are some initiatives aimed at creating global landslide databases such as the EM-DAT International Disaster Database (Guha-Sapir et al., 2014), the Global Landslide Database (Kirchbaum et al., 2010, 2015) and the DesInventar project (UNISDR, 2016). However, due to the local character of instability events, national and regional landslide databases usually provide more reliable and complete information (Damm and Klose, 2015). In recent years, many of these inventories have been developed and enriched worldwide: Australia (Osuchowski, 2008), China (Liu et al., 2013), and especially in Europe, where Van Den Eeckhaut and Hervás (2012) summarized 24 national and 22 regional databases. Many of them have undergone intense development since around 2012, as in the cases of Germany (Damm and Klose, 2015), Slovenia (Komac and Hribernik, 2015), Great Britain (Pennington et al., 2015; Taylor et al., 2015) or the Alps (Wood et al., 2015). Some initiatives have also been developed within the Iberian Peninsula, where slope instabilities constitute important geomorphological hazards (Díaz de Terán et al., 1997), resulting in major social problems with estimated economic losses of 170 million euros per year (Spizzichino et al., 2010). The initiatives include (i) the MOVES Project from the IGME (Instituto Geológico y Minero de España – Geological Survey of Spain) to develop a national landslide database in Spain (Díez-Herrero et al., 2014); (ii) the natural hazard databases developed in Spain (Ayala

Carcedo, 1988), Portugal (Santos et al., 2014; Zêzere et al., 2014) and Andorra (Gallego et al., 2014), which include information about landslides; and (iii) three other regional landslide databases: the Northern Portugal Landslide Database – NPLD (Pereira et al., 2014), the Landslide Database of the Southern Slopes of Sierra Nevada, Granada (Spain) (Irigaray et al., 2007; Jiménez-Perálvarez et al., 2011), and the Cataluña and Principality of Andorra landslide database – LLISCAT (Marco i Planells, 2007).

The Cantabrian Range, which extends along the north coast of Spain, overlooking the Bay of Biscay, from the Basque Country in the east to Asturias in the west, is one of the areas most affected by landslide hazards (Ferrer Gijón, 1987; 1995) and consequential economic losses (Ayala et al., 1987) because of both geological and climatic conditions and high population density. Damage mainly affects communication infrastructures and, to a lesser degree, settlement areas. Existing estimations for the Asturias region (NW Spain) report 66 million euros per year as being the direct total cost of landslides (González Moradas and Lima de Montes, 2001). Despite the high landslide susceptibility of the area, only two regional landslide databases have been developed (Domínguez-Cuesta et al., 1999; San Millán Revuelta, 2015). Particularly notable is the landslide database developed in Asturias by using press archives of the regional newspapers, which allowed the first rainfall threshold for the occurrence of landslides in the Asturian region to be calculated (Domínguez-Cuesta et al., 1999; Francos Garrote, 2011; Domínguez-Cuesta et al., 2012).

3. Study area

The Principality of Asturias is an Autonomous Community in the NW of Spain with an area of ca. 10,600 km^2. 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 characterized by a mountainous relief, with its highest point (Torrecerredo Peak) rising to 2,648 m above sea level (Fig. 1A, B). Most of the population of Asturias is concentrated in and around the three major cities (Oviedo, Gijón and Avilés) and the coal mining area, all located in the centre of the region, while the most peripheral areas have a lower and largely dispersed population.

The bedrock mainly consists of a wide range of folded and fractured Palaeozoic Rocks belonging to two zones within the Iberian Massif (Lotze, 1945): the Cantabrian Zone in the east (Alonso et al., 2009), with a significant presence of calcareous outcrops, and the West–Asturian Leonese Zone in the west (Marcos, 2004), with a predominance of siliceous materials affected by metamorphism (Fig. 1C). In the north and east of the region, this bedrock is covered by a discordant Mesozoic and Tertiary cover (Alonso et al., 1996). The elevation of the Cantabrian Range during the Alpine Orogeny together with the climatic factors conditioned the development of the actual relief through the operation of 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 phenomena of the current geomorphological dynamics. Two generic words denote these instability events in the traditional Asturian dialect: *argayo* and *fana*.

Domínguez-Cuesta et al. (1999; 2012) pointed to precipitation as the main triggering factor for landslides within the study area. The climate in Asturias is characterized by average annual temperature and precipitation of 13.3ºC and 960 mm (Oviedo weather station, 1981–2010) (AEMET, 2012), with maximum and minimum precipitation values in autumn and summer respectively. The average annual number of rainy days per year ranges from 4 (> 30 mm in 24 h) to 30 (> 10 mm in 24 h) and 123 (> 1 mm in 24 h) (Botey et al., 2013). Due to the orientation of the major geographical features (ranges and valleys), the proximity between the sea and the Cantabrian Range, and the prevailing winds, the orographic effect plays a predominant role in the rainfall distribution over the Asturian region (Arasti et al., 2002) (Fig. 1D). Two main precipitation patterns are frequent: (i) frontal rain associated with autumn and winter low pressure systems, or orographic rain due to northern maritime air masses, and (ii) brief episodes of heavy rainfall, due to strong instability of air masses during spring and early summer.

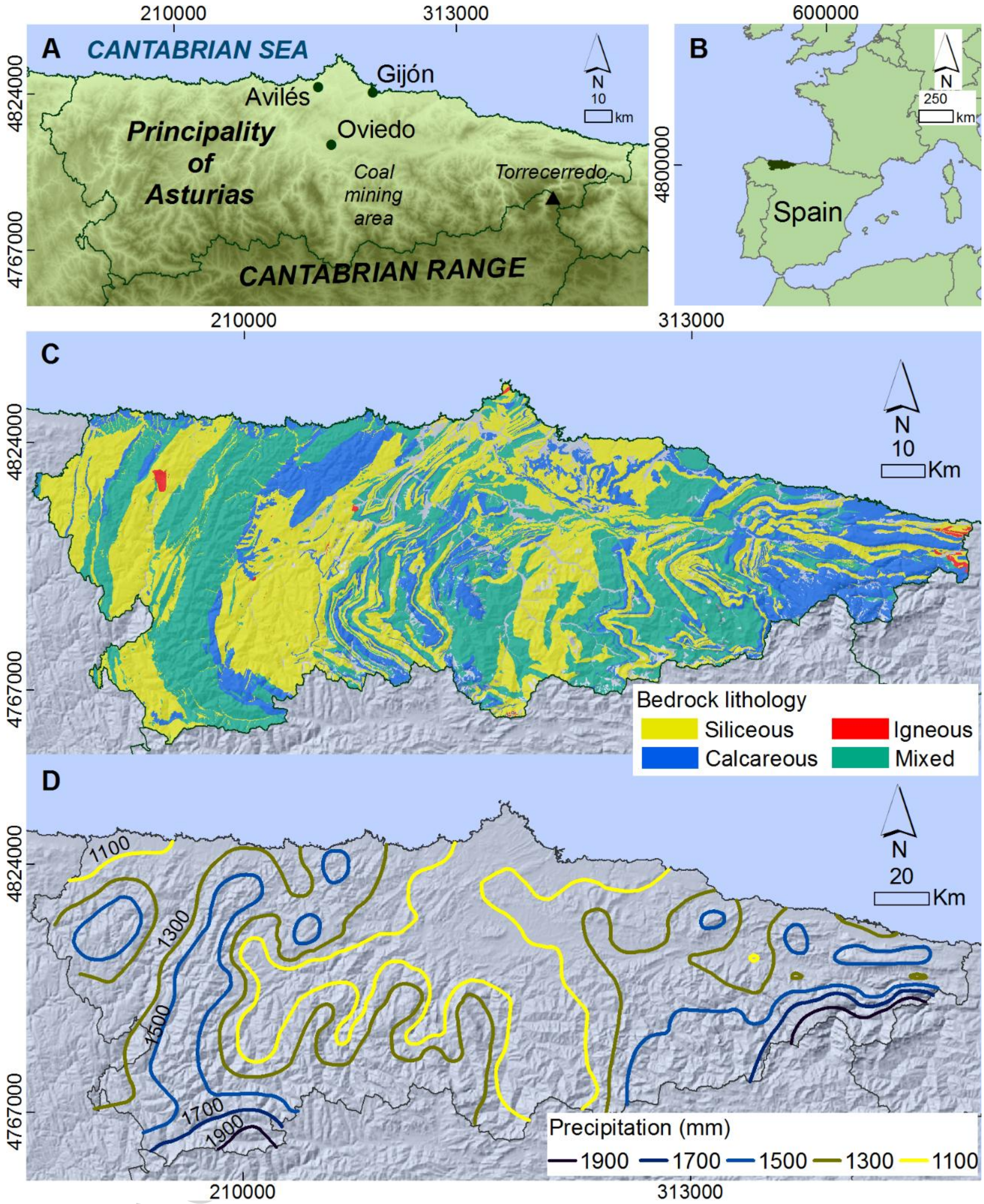

Fig. 1. Characteristics of the study area. **A**. Location of the main geographical features in the study area. **B**. Location of the study area. **C**. Bedrock lithology within the study area, modified from IGME (2004). **D**. Annual isohyet field within the study area, modified from Arasti et al. (2002).

4. Methodology

4.1. Data collection, storage and validation

4.1.1. Selection of data sources

Data collection was mainly based on the review of press archives. *La Nueva España* is the most important regional newspaper, publishing six daily editions, each focussing on a different zones of Asturias. Due to its wide distribution and the increase in its news coverage from the single edition of the 1980s to the current six editions, this newspaper was selected as the main data source. A systematic review of the newspaper library of *La Nueva España* was carried out for the 1980–2015 period. Analogical archives between January 1980 and June 1995 had already been reviewed through visual examination by Domínguez-Cuesta et al. (1999), and they were converted into digital form during the present work. *La Nueva España's* digital newspaper library was used to review digital archives for the period January 1995 to December 2015. This method was chosen instead of visual examination due to the need to review a large amount of newspapers from six different editions within a limited time. Previous experience with analogical archives allowed the selection of the used Spanish keywords: *argayo*, *corrimiento*, *derrumbe*, *deslizamiento*, *desprendimiento*, *grieta*, *hundimiento*, *ladera*, *socavón*, *movimiento* and *avalancha*. Six-months overlap between the analogue and digital periods of records (January 1995 to June 1995) were used to test the efficiency of the data mining through keywords, showing the same results as through visual examination. Once the news items containing at least one of the keywords were selected, a one-by-one visual review was performed to find false positives i.e., when the keyword is used without relation to landslides; e.g. the word *argayo* frequently appears in brand names. Two more regional newspapers (*El Comercio* and *La Voz de Asturias*), together with other mass media (TV and radio), were also considered for the research. These sources were used to crosscheck or to complete the information about landslides previously identified from the main data source.

The use of press archives has some limitations, since the information is biased towards instability events concerning people, infrastructures and human resources, underreporting those that do not cause impacts, occur in uninhabited areas or simultaneously with more conspicuous natural phenomena (Domínguez-Cuesta et al., 1999; Carrara et al., 2003; Guzzetti and Tonelli, 2004; Taylor et al., 2015). For this reason, additional information sources, like reports from citizens and institutions (Natural Park Rangers, *Guardia Civil*–military corps that operate in rural zones, municipalities, and Autonomous Government) have been used to generate a more complete dataset. Initially, the BAPA website (www.geol.uniovi.es/BAPA/) was created to facilitate direct collaboration. Secondly, a BAPA App for Android was developed to take advantage of the widespread use of mobile phones, allowing people to submit geo-located pictures and basic information about the observed landslides (available on Google Play through the keywords "*bapa*" and "*argayo*"). Finally, the BAPA Twitter and Facebook accounts, a leaflet and two informational videos were created to make the project better-known. The BAPA website has been operative since November 2013 and the BAPA App since April 2015.

4.1.2. Database structure

The BAPA database was designed in Microsoft Access. A number is automatically assigned by the software to each entry in the database. Moreover, an ID number is manually assigned for each single landslide identified. This system was adopted for two reasons. (i) It is sometimes difficult to know whether several database entries refer to the same or to different landslides. In this way, the ID number may be modified if the gathering of new data changes the initial interpretation. (ii) The methodology avoids the mixing of data from different sources, which is not desirable even if all the information refers to the same landslide. Thus, several entries could be related to the same landslide and show the same ID number.

Information extracted from raw data was synthesized in 105 different data fields. When possible, drop-down lists (fields with some established options), checkboxes and pre-defined date fields were used to minimize errors during data processing. Moreover, the original text concerning each type of data was also stored in specific fields of "References" within the database to preserve it unchanged, allowing its review in the future. Data were stored in three different formats: text, numeric and image (press archives in the PDF format and photographs in the JPEG format).

Data fields can be grouped in 10 thematic blocks according to the type of information recorded:

1. Registration data: including the automatically assigned number for each entry, the manually assigned ID number for each landslide and a checkbox that indicates if an ID number is linked to one or more entries.
2. Source: date of publication or receipt of the information, type and characteristics of the data source, data format (texts, picture, diagram/map) and information about the person or institution which sent the report.
3. Spatial data: information about the location of the landslide, municipality, nearest town, spatial description, coordinates and road references.
4. Temporal data: year, month, day and moment of the day or exact time of the landslide occurrence.
5. Landslide data: type of landslide, qualitative-quantitative features, type of substratum (shallow deposit, bedrock and artificial deposit), type of slope (natural or artificial) and activity including recurrence.
6. Triggers: data about the triggering factor of the landslide, natural or human-related, with special emphasis on the information about precipitation.
7. Affected infrastructures: including motorway/road, track/path, railway, house, community facility, agricultural/industrial activity, water supply network, sewage network and electricity network.
8. Damage and costs: type of damage (injuries/fatalities or material losses), direct and indirect effects, costs, presence and effectiveness of protection measures and subsequent actions.
9. Accuracy: data accuracy assessment focused on three issues: temporal data, spatial data and landslide data. A numeric field to express the accuracy level was included for each of them.

10. Fieldwork-validation data: the date of the field work and the collected information including the on-site check of the location, time of occurrence and type of landslide, substratum and slope.

4.1.3. Data processing, accuracy assessment and validation

Concerning the usefulness of press archives and personal-institutional reports as landslide data sources, some authors agree that the accuracy of those data is conditioned by various factors, such as the perceptions and skills of different observers and the use of a non-scientific language, which introduce uncertainties (Ibsen and Brundsden, 1996; Domínguez-Cuesta et al., 1999; Zêzere et al., 2014). For this reason, it is necessary to establish some criteria during data processing which allow not only the classification of the information but also the assessment of its accuracy. In this work, particular emphasis was placed on the development of those criteria for the evaluation of the temporal and spatial data as well as the type and characteristics of the landslides.

Despite the lack of information in some cases, a date for each landslide was always recorded and later evaluated. Depending on the availability of detailed temporal information, three date categories were defined: (i) exact date: e.g. “May 16, 1987” and “yesterday” (code in the database = 1); (ii) inferred date: e.g. “two days ago” and “last weekend” (code = 2); and (iii) estimated date: e.g. “a week/month ago” and “last year” (code = 3). Temporal information sometimes includes the exact time of occurrence, which was recorded in the corresponding field. More often, some reference to the moment of the day (morning, midday, afternoon, evening or night) when the landslide took place appears. To translate this timing information into a quantitative form, each day was divided into four periods, taking into account the everyday use of these terms in Spain (e.g. the official end of the morning is 12 pm, but it is commonly considered that the morning lasts until the end of lunch time at 2 pm). To account for the seasonal variation in the length of the day, the four time ranges defined are different between the periods November–April (8 am to 2 pm, 2 pm to 7 pm, 7 pm to 0 am, and 0 am to 8 am) and May–October (7 am to 2 pm, 2 pm to 9 pm, 9 pm to 0 am, and 0 am to 7 am).

The landslide mapping process was based on the spatial descriptions and photos or schemes provided by press archives and reports. Geo-location was carried out by using two free on-line cartographic servers: Google Maps-Google Street View and Iberpix (orthophotos and topographic maps server of Spain at www.ign.es/iberpix2/visor). UTM coordinates were defined for all the identified landslides according to the ETRS89 projection coordinate system and later evaluated. Coordinates included in raw data were checked and converted to the ETRS89 datum. Depending on the precision of the available information, geo-location was performed on three scales: (i) location with exact coordinates (code = 1), supported by precise spatial descriptions and graphical information (associated with 25×25 cm cell size orthophotos equivalent to a 1:1,000 scale); (ii) location with a low to medium level of uncertainty (100–500 m; code = 2), supported by incomplete descriptions or poor quality pictures (associated with 1:10,000 scale maps); and (iii) location with a high level of uncertainty (> 500 m; code = 3), supported by very scarce general data (associated with 1:25,000 scale maps or greater).

The landslide type was determined taking into account the available graphical information. On the basis of Cruden and Varnes’s (1996) classification, three categories were designed: “rockfall”, “slide”, and “flow”; and two more categories were added to indicate precursory signs of a slope instability: “crack” and “subsidence/collapse”. The accuracy of the assigned type in each case was expressed with numbers: 1 = high (supported by high quality pictures or field work), and 2 = low (supported by low quality pictures).

Field work was conducted to validate the dataset, allowing the review of (i) the location and characteristics of the recorded landslides (types of landslides, slopes and affected substratum), and (ii) the temporal data obtained by questioning to the inhabitants of the area. Ten per cent of the recorded locations were reviewed through on-site visits. Seven field work campaigns were performed in different areas to cover representative samples of the region: western coast, western mountains, central coast, central mountains, capital area, eastern coast and eastern mountains. During the campaigns, the local road network was followed, reviewing all the previously identified landslides located in the areas close to the selected route.

4.2. Data analysis

Basic queries to the BAPA database were used to perform the first analysis of the recorded dataset. Afterwards, the original Microsoft Access files were exported to Microsoft Excel and ArcGIS 9.3 to graphically display the results. Temporal variation of the number of records throughout the study period were estimated and interpreted following the methodology described by Guzzetti (2000) and Rossi et al. (2010). The number of landslides per day (Ls dy^{-1}) and the gradient of the curve showing the cumulative number of reported landslides per year were used as proxies of the intensity of landsliding and the completeness of the database, respectively. The influence of the additional data sources was also considered (reports, BAPA website and BAPA App).

Spatial distribution of the landslides and its change with time were analysed in relation to some conditioning factors, such as geology and population density. Attention was also paid to interpretation of the variation of the spatial and temporal data accuracy levels from 1980 to 2015. Finally, to assess the reliability of the data about triggers, a preliminary analysis of the BAPA dataset together with monthly precipitation data series was conducted. As proposed by Pereira et al. (2014) and Damm and Klose (2015), the Pearson's correlation coefficient was used to express the dependence between landslides and rainfall. Precipitation data series from 15 AEMET (Agencia Estatal de Meteorología – Spanish Meteorological Agency) weather stations, covering a period of 36 years (1980–2015), were used to calculate average monthly precipitation values for the region.

5. Results

As a result of data collection, 2073 individual landslides were identified with ID numbers and stored in the BAPA database. Almost all of them (2063) took place during 1980–2015 and were selected as the study target dataset; the remaining 10 landslides are isolated records from the previous years and were excluded from the present analysis. Among the stored landslides, 241 were identified by using information from multiple sources; consequently, there is more than one entry within the database related to them. In the remaining 1822 cases, each entry refers to a single landslide. A total of 2379 entries were entered into the database. About 88% of the extracted information (2106 entries) came from the review of 7600 press archives of regional newspapers, radio and TV, and the remaining 12% (273 entries) came from 341 reports sent by individual citizens and institutions (*Guardia Civil*, Natural Park Rangers, Autonomous

Government and Municipalities) (Fig. 2). Information from reports is only available for years 2001–2015, while data from journalistic sources covers the whole period of study. *La Nueva España* newspaper was the most frequently used press source (1940 entries). Moreover, *El Comercio* and *La Voz de Asturias* newspapers (164 entries) together with the radio and TV (two entries) were used to crosscheck or complete the information about landslides previously identified from *La Nueva España* newspaper in 95% of the cases. Only in 5% of the cases, new landslides unreported in *La Nueva España* were identified. Most of data extracted from reports were obtained through direct personal communication (200 entries). The implementation of the BAPA website and the BAPA App allowed to collect some additional information (73 entries) from November 2013 to December 2015. Data from reports allowed the identification of 235 landslides unreported in the journalistic sources. Finally, 223 landslides were visited *in situ* as a part of the validation process.

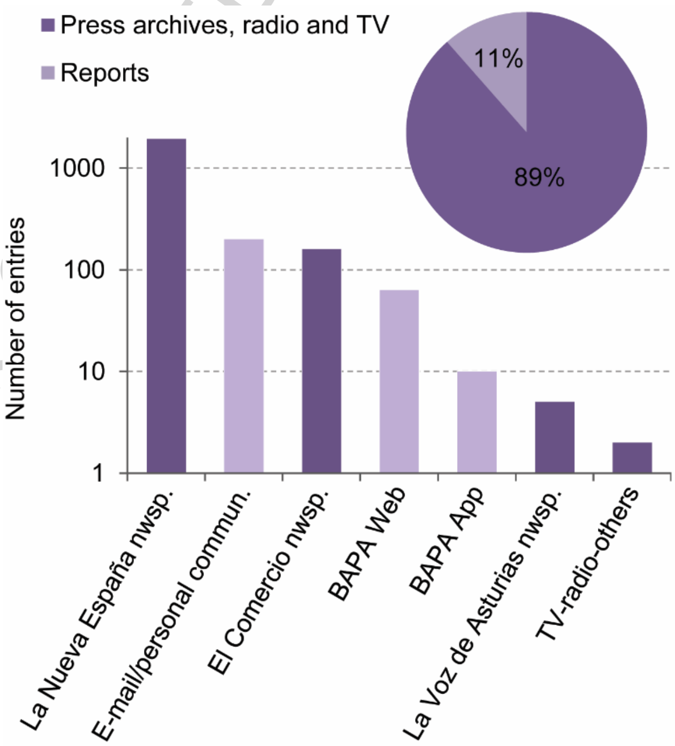

Fig. 2. Information sources used for the identification of the collected landslides.

5.1. Characteristics of spatial data

Fig. 3A represents the spatial distribution of the BAPA dataset within the territory of Asturias. The central area shows the highest density of records, followed by the eastern area, while the western area registers the lowest number of recorded instabilities. Moreover, 68% of the records (1402 landslides) are located along the regional road network. The landslides identified from press archives, radio and TV cover the whole study area. However, the dataset shows an irregular distribution; the municipalities which have more than 41 records are more numerous in the eastern area and the municipalities with more than 66 landslides are concentrated in the central area (Fig. 3B). By contrast, the landslides from the reports show a more irregular distribution over the study area, with the highest concentration of records in a few scattered municipalities. Fig. 3C illustrates the density of landslides per municipality based on the whole BAPA dataset; two municipalities located in the central coastal area reached the highest values for this parameter, between 1.14 and 1.68 Ls km^{-2}, and the other eight municipalities, located in the central and eastern areas of Asturias, had values between 0.37 and 1.14 Ls km^{-2}. A comparison between the density of landslides and the population density in each municipality (Fig. 3D) shows a high degree of coincidence between the two. The highest landslide densities also correspond to the locations of the offices of the newspaper *La Nueva España*, the main data source used in the present research. Finally, the BAPA dataset was divided into 6-year periods and the landslides that occurred during these intervals were plotted on individual maps (Fig. 4) to show the change in the spatial distribution during 1980–2015. The highest concentration of records is observed to be in the central area throughout the studied period. After 1992, the number of landslides recorded in the peripheral areas of Asturias increases, especially in the eastern zone. It is only from 2004 that the number of recorded landslides increases in the western area; most of these data come from personal reports, the BAPA website and the BAPA App.

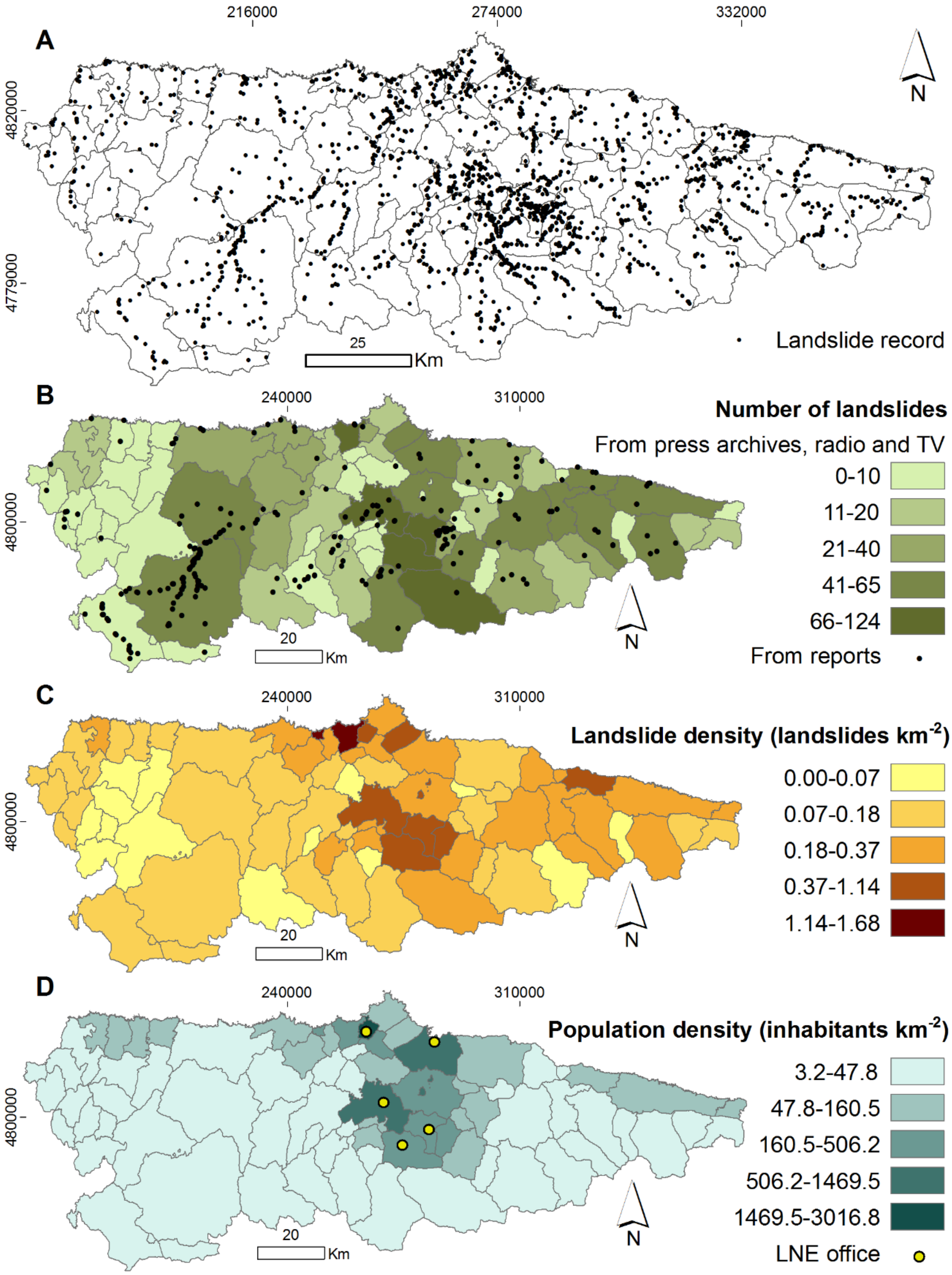

Fig. **3**. Characteristics of the spatial data. **A**. Spatial distribution of the BAPA dataset throughout the Principality of Asturias. **B**. Comparison between the number of records from press archives per municipality (polygons) and records from reports (points). **C**. Landslide density for each municipality. **D**. Population density for each municipality and location of the offices of the newspaper *La Nueva España* (data from INE, 2015 and *La Nueva España*, LNE).

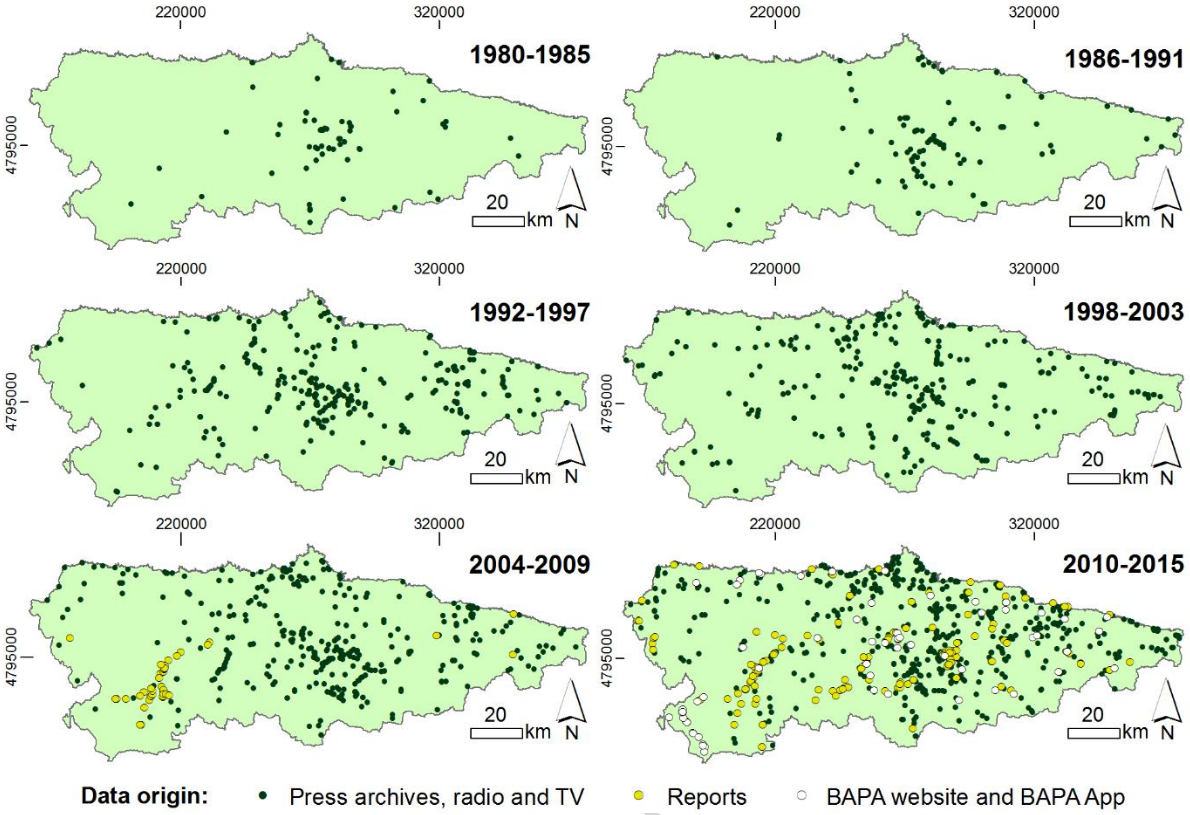

Fig. **4**. Temporal change in landslide distribution based on the BAPA dataset during 1980-2015 within the Principality of Asturias.

After the geo-location process, high spatial accuracy (level 1) was assigned to 1217 landslides (59%); 491 landslides (24%) were assigned to medium accuracy (level 2) and the remaining 355 landslides (17%) to low accuracy (level 3). Fig. 5A shows the change in the spatial accuracy during the period 1980–2015. The number of records with the highest accuracy tends to increase significantly with time, while the numbers of records with the medium and low accuracy levels show a more moderate growth. Moreover, the records within each accuracy level show quite even distributions over the study area (Fig. 5B).

A validation process through field work confirmed the initial assessment of the spatial accuracy in 83% of the visited landslides. In the remaining cases, field work led to an increase in the accuracy level (11%) or a decrease (6%) (Fig. 5C). Fig. 5D shows the percentage of initial spatial accuracy assessments that were confirmed during the validation process. High percentages of validated cases were reached for level 1 (92.8%) and level 3 (79.3%), while that percentage decreases for level 2 (58.9%). About 63% of the records with the highest accuracy include photos or schemes, while this share decreases drastically for those with medium or low accuracy (Fig. 5D).

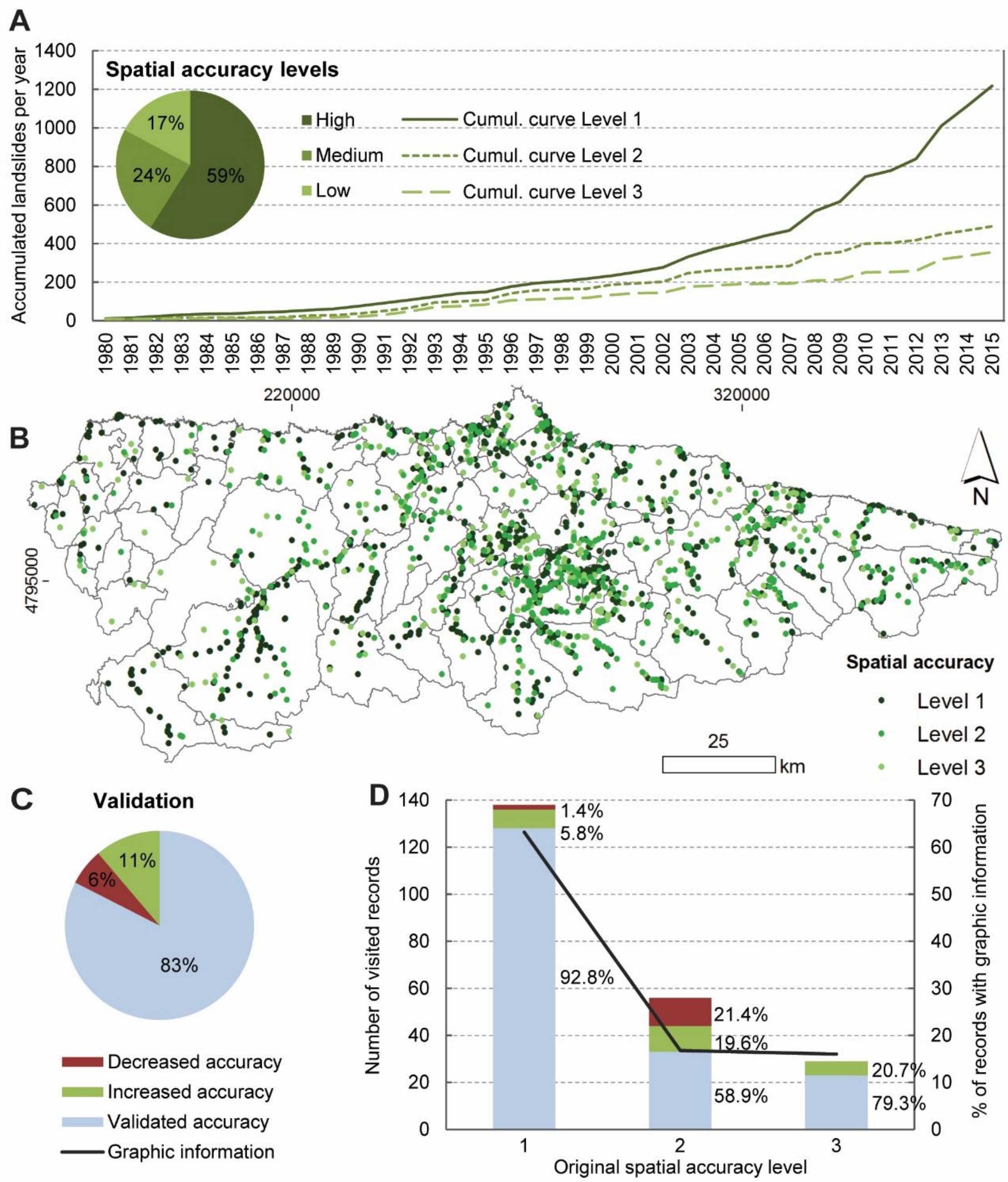

Fig. **5**. Analysis of spatial accuracy. **A**. Variation of the spatial accuracy over the study period. **B**. Distribution of the spatial accuracy over the study area. **C**. Total results of the validation process. **D**. Results of the validation process within the three established accuracy levels in relation to the availability of graphical information in database records shown by the line.

5.2. Characteristics of temporal data

The number of landslides per day between 1980 and 2015 ranges from 0 to 62. During this period of 13,149 days, 992 days (7.54%) had at least one landslide, 61 days (0.46%) had 5 or more landslides, and 27 days (0.21%) had 10 or more landslides (Table 1).

Parameter	Value	Unit	Period	Date
Maximum number of landslides in a day	62	Ls dy^{-1}	1980-2015	16/11/200
Minimum number of landslides in a day	0	Ls dy^{-1}	1980-2015	---
Number of days with landslide records ≥ 1	992	dy	1980-2015	---
Number of days with landslide records ≥ 5	61	dy	1980-2015	---
Number of days with landslide records ≥ 10	27	dy	1980-2015	---
Maximum number of landslides in a year	262	Ls yr^{-1}	1980-2015	2013
Minimum number of landslides in a year	1	Ls yr^{-1}	1980-2015	1985
Average number of total landslides per year	57.3	Ls yr^{-1}	1980-2015	---
Gradient of the cumulative curve of reported	9.4	Ls yr^{-1}	1980-1990	---
landslides from press, radio and TV	47.0	Ls yr^{-1}	1991-2007	---
	105.7	Ls yr^{-1}	2008-2015	---
Gradient of the cumulative curve of total	9.4	Ls yr^{-1}	1980-1990	---
reported landslides	47.5	Ls yr^{-1}	1991-2007	---
	136.6	Ls yr^{-1}	2008-2015	---

Table 1. Characteristics of the BAPA temporal dataset

Fig. 6A represents the temporal distribution of the recorded landslides during 1980–2015. The time series shows a long-term increase in the annual frequency of landslides, superimposed by strong annual fluctuations ranging from 1 to 262 landslides in a year, with an average of 57.3 landslides per year. Two cumulative curves show (i) the number of reported landslides from press archives, radio and TV, and (ii) the number of all reported landslides. Taking into account the slope changes observed in both curves in 1990 and 2007, the dataset was divided into three periods. 1980–1990, 1991–2007 and

2008–2015. For each period, the gradient of the best-fit straight line, interpreted as the rate at which landslides were reported in Ls yr^{-1}, was calculated for both cumulative curves (Table 1). The first time period covers 30.5% of the total time series (11 years) but only includes 6.4% of the total identified landslides (133 records from press, radio and TV), and the number of landslides per year is always above the average value of 57.3 Ls yr^{-1} calculated for the study range. The second time period covers 47.2% of the studied range (17 years) and includes 39.3% of the total identified landslides (790 records from press, radio and TV and 21 from reports), showing 4 years with a number of landslides per year over the average. The third and shortest time period, which corresponds to 22.3% of the time series (8 years), includes 54.32% of total landslides (884 records from press, radio and TV and 235 from reports), showing only one year with a number of landslides below the average.

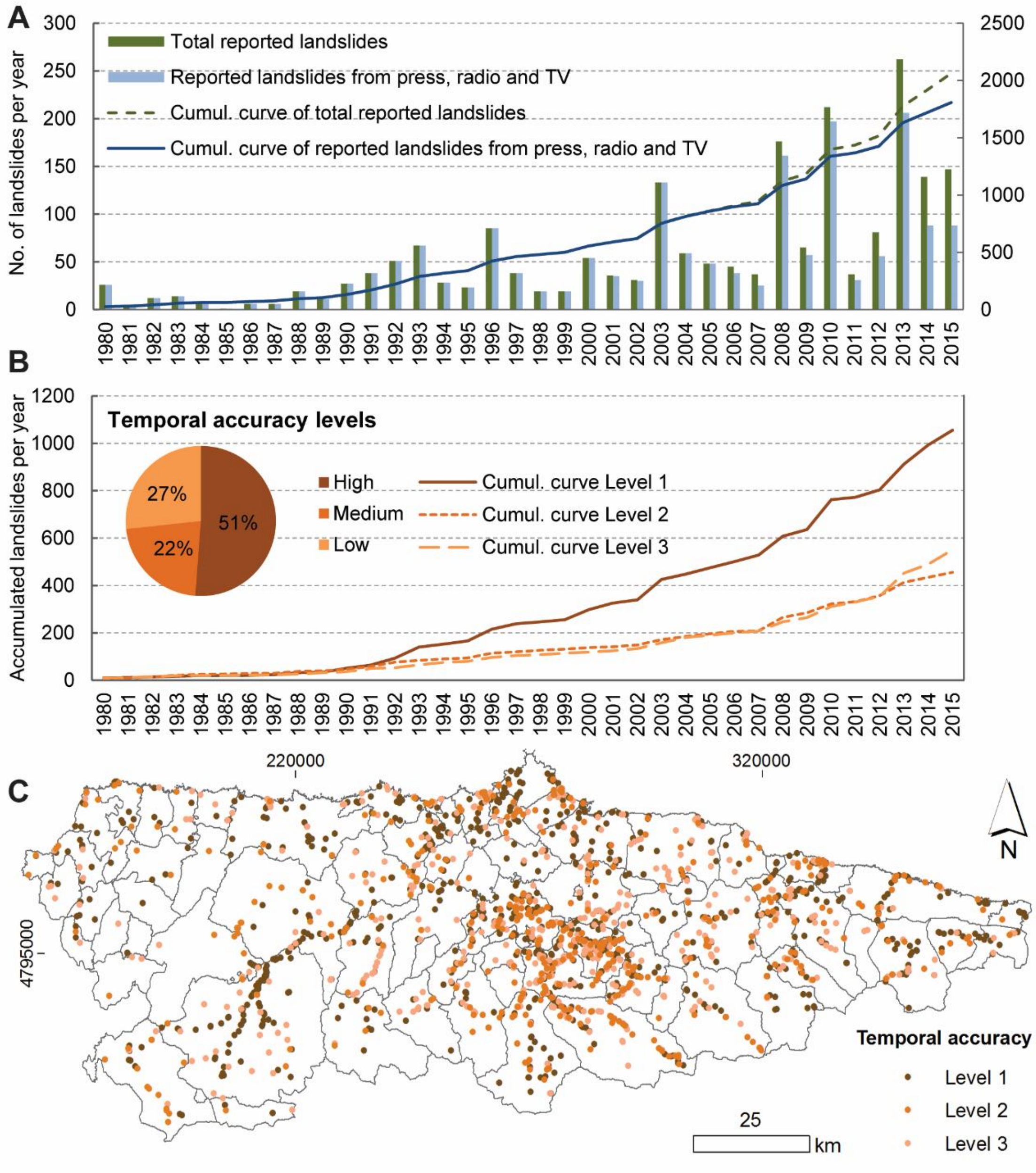

Fig. **6**. Characteristics of the temporal data. **A**. Temporal distribution of the recorded landslides during 1980–2015. **B**. Variation of the temporal accuracy over the study period. **C**. Distribution of the temporal accuracy levels over the study area.

Assessment of temporal accuracy over the BAPA dataset indicated that 1056 records (51%) were assigned to the maximum level of accuracy (level 1), 456 records (22%) to the medium level (level 2) and the remaining 551 landslides (27%) to the lower level (level 3). Within the highest accuracy level, the exact time of occurrence is known for

273 landslides and the moment of the day for 475 landslides. Fig. 6B shows the variation in the number of landslides within each of the levels of temporal accuracy for 1980–2015. While the number of landslides within the temporal accuracy level 1 increases in parallel with the increasing number of records during the study period, the number of landslides with the accuracy levels 2 and 3 present a more moderate growth, only showing a significant increase in the trend from 2008 to present. Fig. 6C shows a quite even distribution of the records for the three accuracy levels over the study area. Surveys conducted with the inhabitants of the area performed during the field validation process confirmed the date of occurrence in less than 1% of the cases. In the rest of the cases, no reliable information could be gathered.

5.3. Characteristics of landslide properties

The type of landslide was determined in 45% of the records (927 landslides): 26% were classified as rockfall, 11% as slide, 5% as flow and 3% showed some precursory sign of slope instability (subsidence/collapse or crack). This classification could not be performed in the remaining 55% (1136 landslides) (Fig. 7A). Affected materials could be determined in 37% of the records (759 landslides) and remained undetermined in 63% (1304 landslides). Bedrock was affected in 12% of the cases, natural shallow deposits in 10%, 12% involved both bedrock and natural shallow deposits, and 3% involved materials of anthropic origin (heap deposits or fill material) (Fig. 7B). Moreover, 32% of the recorded landslides (655) took place in artificial slopes related to roads and other human infrastructures, while only 14% of them (293) occurred on natural slopes, and the type of slope remained undetermined in 54% of the landslides (1115) (Fig. 7C). Detailed qualitative data about the type of affected material or the size of the landslides were available for 38% of the cases (782 landslides), and quantitative data related to the dimensions of the landslide or the volume of remobilized material were available only for 10% (208 landslides). Evidence of recurrence was recorded for 208 landslides. Finally, data about the level of activity after the triggering of the slope instability were only recorded for 70 landslides. The validation process through field work confirmed the initial characterization of: (i) the type of instability in 78% of the records, (ii) the affected substratum in 73% of the records, and (iii) the affected slope in 77% of the records. In the remaining cases, this initial information was modified using the data collected *in situ* (Fig. 7D).

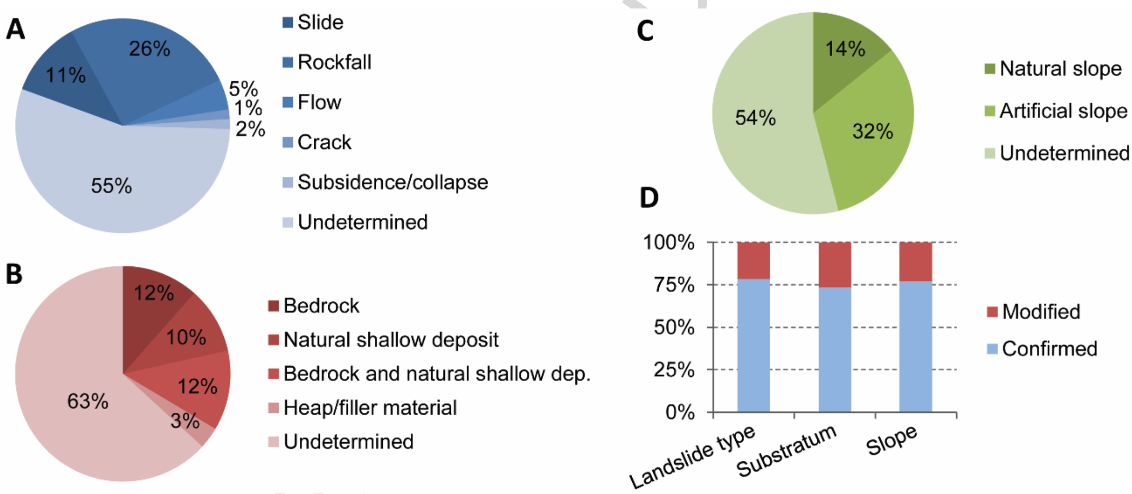

Fig. **7**. Characteristics of the recorded landslides. **A**. Type of landslide. **B**. Type of substratum affected. **C**. Character of the slope. **D**. Results of the validation of previous data through field work.

5.4. Triggering factors

A total of 1455 records provided data about triggers: 83% of them were attributed to natural factors, 9% to anthropogenic factors, and 8% to both natural and anthropic factors; no data about triggers were available for the remaining 608 landslides. The stored information indicates that 1232 landslides were attributed to rainfall.

The comparison between the monthly landslide records gathered on the BAPA database for 1980–2015 and monthly precipitation data highlighted the cyclical fluctuations in the monthly frequency of landslides due to seasonal variations in precipitation; those fluctuations may be observed clearly after 2000 and are particularly well-defined since 2012 (Fig. 8A). All the months with the highest landslide records coincide with high monthly rainfall values based on the moving average calculated for 5 months; the most remarkable cases are November 2008 (255 mm; 83 records), June 2010 (275 mm; 163 records) and January–February 2013 (266+256 mm; 143 records) (Fig. 8A). However, not all the months with high rainfall values show a significant number of landslides, especially between 1980 and 1990. Correlation coefficients between precipitation and landslides calculated for 1980–1990 (R^2 = 0.18), 1991–2007 (R^2 = 0.30) and 2008–2015 (R^2 = 0.56) showed a positive correlation at a monthly scale, with increasing R^2 values since 1980. Landslide distribution throughout the hydrological year is represented in Fig. 8B, showing a positive correlation (R^2 = 0.62) between average monthly precipitation and total monthly landslide records for 1980–2015 (Fig. 8C). Landslides in Asturias mostly occur from October to April while their frequency decreases during the period from May to September. January is the month with the highest number of landslides (294) and July is the month with fewest records (46). Different landslide datasets were defined according to their natural or human triggering factors, and their distribution throughout the hydrological year was plotted in Fig. 8D. Additional correlation coefficients between average monthly precipitation and landslide records were calculated taking into account only the landslide dataset triggered by (i) natural causes (R^2 = 0.59), (ii) rainfall (R^2 = 0.60), and (iii) anthropogenic causes (R^2 = 0.64) (Fig. 8E).

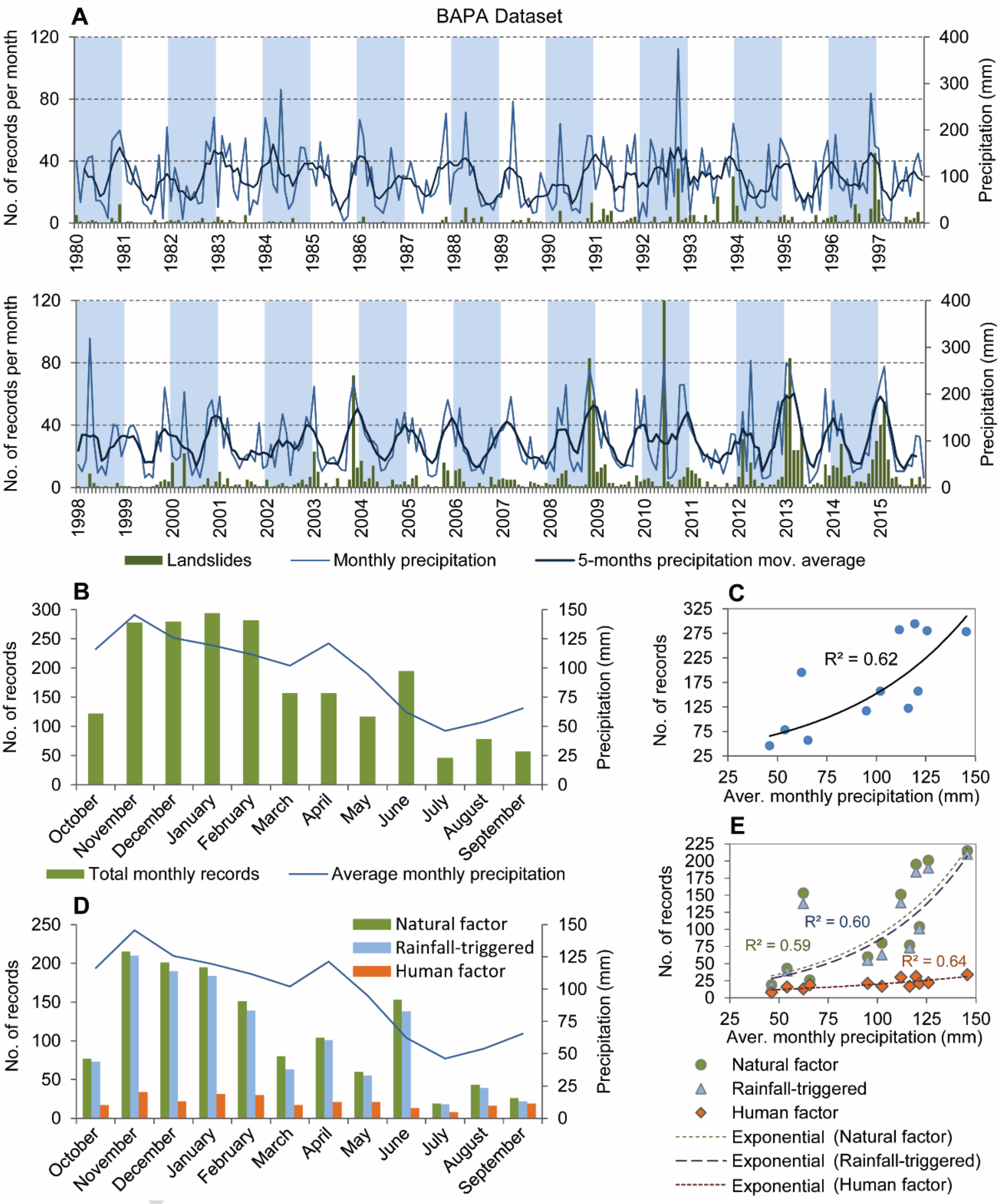

Fig. **8**. Characterization of the relation between landslides and rainfall. **A**. Monthly distribution of the BAPA dataset during 1980–2015. **B**. Landslide distribution during the hydrological year. **C**. Correlation between total monthly landslide records and average monthly precipitation. **D**. Monthly distribution of the landslides during the hydrological year according to its triggering factor. **E**. Correlation between monthly landslide records with different triggering factors and average monthly precipitation.

5.5. Damage and costs

At least 87% of the landslides gathered in the BAPA database (1801 records) produced some kind of damage (Fig. 9A), including 1762 landslides causing material losses (97.8%), 13 landslides causing injuries and fatalities (0.7%) and 26 landslides causing both material losses and injuries/fatalities (1.4%). Moreover, 58.6% of the landslides that caused material losses provoked direct effects (damage to property and infrastructures), 1.6% provoked indirect effects (road closures, people evacuated, suspension of the transport services or interruptions in the industrial production) and the remaining 39.8% caused both direct and indirect effects. Some kind of previous protection measure existed in 69 of the landslides that caused damage, although those measures were effective only in 14 of the cases. Landslides mainly affect the communications network: motorways and roads (72%), paths and pedestrian access (7%) and the railway network (3%), followed by damage to houses (6%) and to the water supply network (4%) (Fig. 9B).

In many cases, remedying landslide damage implies large economic investments. An estimation of the costs was calculated by considering the information appearing in newspapers. Fig. 9C shows the frequency of different levels of repair expenditure, based on the budgeted costs of 135 instability events gathered in the BAPA dataset. When there were discrepancies between the amounts of the budget shown by different sources for the same landslide, the calculation was performed considering the highest one. The average repair expenditure per landslide is of 202,232 €. However, in 55% of the cases where data are available, the budgets are lower than 100,000 € and only two of them reach figures higher than 1,000,000 €.

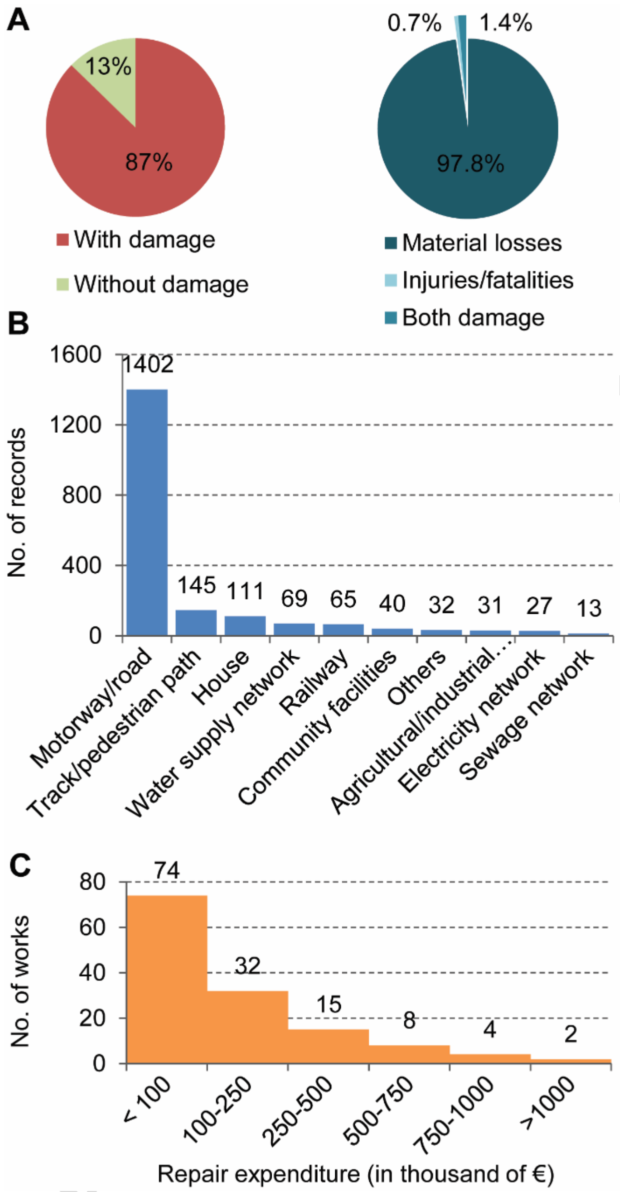

Fig. 9. Damage and costs caused by the recorded landslides. **A**. Percentage of landslides causing damage, material losses or injuries/fatalities. **B**. Affected infrastructures. **C**. Amount of repair expenditure.

6. Discussion

The analysis of temporal distribution of the BAPA dataset pointed to a significant long-term increase in the annual and monthly numbers of recorded landslides since 1980. Precipitation records for the same period show no equivalent incremental trend (Fig. 8A). Thus, the main cause for this trend is not climatological. However, high precipitation values recorded in some recent wet years, such as 2008 (1448 mm) and 2013 (1517 mm), may explain a short-lived increase in the number of landslides. Because 88% of data used came from press archives, radio and TV, the growth in the rate of reported landslides has been associated with the expansion of the regional journalistic sources. In relation to this, the scarcity of data during 1980–1990 was related to the limited number of editions of the regional newspapers; the availability of data increased between 1991 and 2007 with the progressive creation of specialized editions of *La Nueva España* for different zones in Asturias and the development of digital editions of the regional newspapers on the Internet. Furthermore, the emergence and wide use of Facebook and other social media since 2008 has increased the availability of information, which is then often reflected in the newspapers.

With respect to the variation in availability of data in the press archives, the BAPA database shows a temporal bias towards more recent landslides, when more records with high temporal accuracy were gathered. The database may be considered reasonably complete for the period 2008–2015, as evidenced by the regular increase in the number of reported landslides with time at a rate of 105.7 Ls yr^{-1} (Fig. 6A). Such an increase is lower for 1991–2007 (47.0 Ls yr^{-1}) and 1980–1990 (9.4 Ls yr^{-1}), considered as relatively incomplete and highly incomplete, respectively. This fact explains the lack of landslide records in some months with high accumulated precipitation values before 2008. Additional landslide records collected from personal communications, together with the records reported from the BAPA website and the BAPA App, contributed to increasing the completeness of the database; considering these data, the rate at which landslides were reported increased to 136.6 Ls yr^{-1} after 2008. The improvement in the completeness of the dataset, together with the identification of 235 new landslides unreported by press archives, supports the usefulness of the collaboration with citizens and institutions to reduce the bias of the database.

The proposed methodology of validation through field work did not prove to be useful in validating the accuracy of the temporal information. With a few exceptions, the people consulted could only remember the month or the year when the landslide took place. Only when the respondent suffered direct damages were data about the day or the hour of occurrence provided. In contrast, the systematic recording of data in the newspapers, published soon after the occurrence of landslides, preserved detailed temporal data. Thus, press archives are considered as the most reliable source of temporal information for the study area.

Regarding the spatial distribution of the BAPA dataset, the high density of landslides recorded in some areas could be attributable to geological or geomorphological factors. For example, the presence of unstable cliffs and marine erosion along the coastline and the bedrock with highly altered materials in the central area (Figs. 1 and 3A). However, given the high proportion of data from newspapers, the observed landslide distribution is definitely not dependent on natural factors. This inference is consistent with some alignments of landslides plotted in the map (Fig. 3A), especially in the SW and S areas of Asturias, along main roads. Observed correlations among the number of recorded landslides from press archives, radio and TV (Fig. 3B), landslide density (Fig. 3C) and population density (Fig. 3D) in each municipality also support this. In the central area, the greatest abundance of records seems to occur in the proximity of *La Nueva España* offices (Fig. 3D), allowing journalists to easily access the information. As usual in newspaper based landslide inventories, the BAPA database presents a bias towards populated and accessible areas (Zêzere et al, 2014; Taylor et al., 2015). For this reason, the resulting map may misrepresent the real landslide distribution in Asturias. Observed variations in the spatial distribution of the BAPA dataset (Fig. 4) also reflect the increase in information due to the expansion of the regional journalistic sources. From 1980 to 1991, the existence of single editions of the regional newspapers in the major cities justifies the concentration of records in the central region of Asturias; the progressive creation of local editions of *La Nueva España* increases the number of reported landslides from press archives during the period 1992–2003; but only after 2010 did the additional data from reports, the BAPA website and BAPA App provide a reasonably homogeneous distribution of landslides in the study area.

Field work was proved to be very useful in validating the accuracy of the spatial information. Previously defined spatial accuracy levels were confirmed in 83% of the visited cases, which verified the high reliability of the information in the BAPA database and confirmed the usefulness of press archives and cartographic servers for identifying and locating landslide events. Fig. 5D shows the relationship between the availability of photos and the landslide record spatial accuracy level. A significant percentage (63%) of the records with the spatial accuracy level 1 was located thanks to the availability of graphical information availability, especially from Google Street

View. In contrast, less than 20% of the records with spatial accuracy levels 2 and 3 included landslide photos. Regarding the validation process, the percentage of confirmations of the initial spatial accuracy assessment was higher for the records of level 1 (92.8%) and level 3 (79.3%) than for level 2 (58.9%). The abundant spatial information in the level 1 but not in the level 3 made it difficult to improve the spatial accuracy through a field visit.

The widespread use of the traditional terms *argayo* and *fana* in Asturias, together with the journalistic use of the words slide, rockfall and flow as synonyms, makes it difficult to apply a genetic classification of the recorded landslides. Data about the substratum and the natural or artificial character of the affected slope is frequently uncertain due to the limited technical experience of the informants and journalists. Although photos included in press archives or reports are found to be a valuable source of genetic and geological information, they often show only a partial vision of the event so the geological and genetic characteristics could be defined in less than 50% of the cases. However, validation through field work proved the accuracy of those data in 75% of cases. Conversely, data about the size of the event, recurrence and level of activity are insufficient to allow any statistical examination. Finally, the scarcity of data for events occurring in natural slopes implies a bias towards slopes modified by human activities.

High density of landslides does not correspond to high average annual rainfall at the regional scale (Figs. 1C and 3A). Conversely, the monthly landslide records and monthly precipitation are correlated, especially during the most complete period of the dataset (2008–2015) with R^2 = 0.56 (Fig. 8A). A better correlation (R^2 = 0.62) was obtained between average monthly precipitation and the total number of landslides per month (Fig. 8B, C). Intense landslide activity from October to February is related to long rainfall episodes associated with major autumn and winter low pressure systems or persistent orographic rain due to the activity of northern maritime air masses. June shows an unusually large number of records in spite of the low average monthly precipitation (62 mm). The occurrence of brief periods of heavy rainfall, such as heavy convective precipitation and thunderstorms, is responsible for this. A particularly intense rainfall event took place in June 2010 (Fig. 8A): a quasi-stationary low pressure centre over the Cantabrian Sea and a mid-level cold air pool gave rise to strong thermal and dynamic instability; two short-lasting but heavy convective rainfall events between 8 and 16 June triggered at least 164 landslides. Removing this outlier case, the correlation improves from R^2 = 0.62 to 0.82.

Journalists and citizens often provide unclear data concerning natural factors, such as rainfall, and tend to focus on problems with infrastructures (García-Urquia and Axelsson, 2014). However, a positive correlation between the number of natural landslides in the BAPA database and average monthly precipitation indicates that such data are still useful. Their correlation even increases from R^2 = 0.59 to 0.60 if landslides due to factors other than rainfall, such as fluvial or coastal erosion, are removed. Finally, a positive correlation (R^2 = 0.64) between average monthly precipitation and the number of landslides triggered by human factors was observed. This result highlights the influence of rainfall as a conditioning factor even for non-natural instability events. In summary, rainfall is the main triggering factor of landslides in Asturias, which agrees with previous research (Domínguez-Cuesta et al., 1999; Francos Garrote, 2011; Domínguez-Cuesta et al., 2012). However, more detailed analysis is needed in order to better characterize the role of rainfall.

While landslides producing personal injuries or fatalities are unusual in the study area, economic damage is often caused. However, the total expenditure by local and regional administrations on repair and maintenance work has not been officially reported in Asturias. Therefore, this analysis has made use of the most detailed available estimation of direct costs. A more realistic estimation of costs would require data about the indirect costs related to various aspects such as evacuation of people, suspension of transport services and interruptions of industrial production.

7. Conclusions

The BAPA database gathers information about 1828 landslides identified from press archives, radio and TV for the period 1980–2015, and 235 landslides from reports sent by citizens and institutions during 2001–2015. The use of additional data sources including personal communication, the BAPA website and the BAPA App was found to be useful in minimizing the bias caused by the use of journalistic information and improving the completeness of the database, especially since 2008.

Field work was also confirmed to be useful to correctly locate landslides and assess the accuracy of spatial information from text descriptions and photos as well as online cartographic services, including Google Maps and Iberpix. Temporal data from press archives were found to be the most reliable source for Asturias, whereas questionnaire surveys to the inhabitants were not particularly useful to obtain accurate temporal information. Despite some scarcity and bias in the information, the BAPA database is suitable for performing preliminary analyses including cost estimations.

The positive correlation between monthly precipitation and the number of landslides, even for cases where human triggering factors played a role, confirmed the strong influence of rainfall on slope instability in the study area. A significant number of landslide records (654 records) show accurate spatial locations as well as temporal information about the occurrence on daily and hourly scales, making the data suitable for detailed correlations with climatic factors.

ACKNOWLEDGEMENTS

This research is funded by the Department of Employment, Industry and Tourism of the Government of Asturias, Spain, and the European Regional Development Fund FEDER, within the framework of the research grant "GEOCANTABRICA: Procesos geológicos modeladores del relieve de la Cordillera Cantábrica" (FC-15-GRUPIN14-044), and supported by the cooperation between the Department of Geology at the University of Oviedo and the AEMET. The development of the BAPA App was sponsored by the FECYT, Government of Spain. The authors gratefully acknowledge the selfless cooperation of the newspapers *La Nueva España* and *El Comercio* and the citizens and institutions which have contributed to the development of the BAPA database. Finally, the authors are grateful for the comments of C. Xu and another anonymous referee, who greatly helped to improve the manuscript, and the support provided by A. Vega, D. Moral and D. Ballesteros.

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HIGHLIGHTS

- BAPA is a new landslide database developed in Asturias (NW of Spain).
- 2063 landslides were recorded between January 1980 and December 2015.
- Data comes from press archives and reports from citizens and institutions.
- Spatio-temporal data accuracy is checked through cartographic servers and field work.
- The database includes data about landslide characteristics, triggers, damage and costs.