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Regional reconstruction of flash flood history in the Guadarrama range (Central System, Spain)

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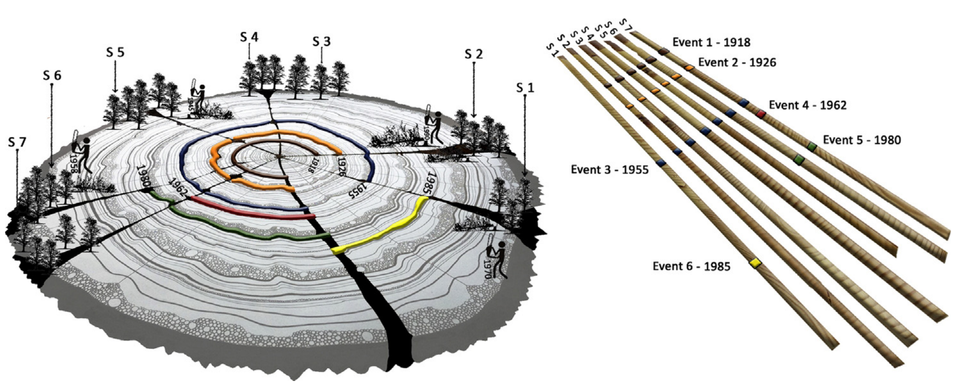
HIGHLIGHTS

- Flash floods represent a regional natural hazard in Guadarrama range.
- Dendrochronology allows fill the lack of systematic data in mountain environments.
- Regional studies and quality samples allow reducing the number of collected samples.
- We complement existing records with 8 events covering the last ~200 years.
- Forest management could limit the amount of proxy evidence of flash flood events.

GRAPHICAL ABSTRACT



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ABSTRACT

Flash floods are a common natural hazard in Mediterranean mountain environments and responsible for serious economic and human disasters. The study of flash flood dynamics and their triggers is a key issue; however, the retrieval of historical data is often limited in mountain regions as a result of short time series and the systematic lack of historical data. In this study, we attempt to overcome data deficiency by supplementing existing records with dendrogeomorphic techniques which were employed in seven mountain streams along the northern slopes of the Guadarrama Mountain range. Here we present results derived from the tree-ring analysis of 117 samples from 63 *Pinus sylvestris* L. trees injured by flash floods, to complement existing flash flood records covering the last ~200 years and comment on their hydro-meteorological triggers. To understand the varying number of reconstructed flash flood events in each of the catchments, we also performed a comparative analysis of geomorphic catchment characteristics, land use evolution and forest management. Furthermore, we discuss the limitations of dendrogeomorphic techniques applied in managed forests.

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1. Introduction

Flash floods are natural processes in mountain environment and typically triggered by intense, but short-lived precipitation events (Borga et al., 2014). The process is characterized by its sudden occurrence combining high stream power and sediment transport rates

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which make it one of the most harmful natural hazards in mountain and hillslope environments (Borga et al., 2008, 2014; Marchi et al., in press). Recent studies suggest that climate change may have an impact on the triggering of flash floods and that the occurrence may increase at the global scale (Beniston, 2009; Giorgi et al., 2011). Specifically in Spain, Benito (2006) and Benito et al. (1996, 2015) have reported on the flood sensitivity of Spanish rivers to climate change and suggest that variations in climate characteristics may increase the irregularity of the flood regime and droughts and thereby favor the generation of flash floods in Mediterranean basins. Changes in precipitation may have a direct impact in the future occurrence of extreme hydrological events (Beniston et al., 2011; Gobiet et al., 2014; Stoffel and Huggel, 2012; Stoffel et al., 2014a), which could in turn affect the future development of mountain environments (Beniston et al., 2012). In this context, flash flood processes in mountain environments could become an important issue in Mediterranean environments over the next few decades (Borga et al., 2014).

Nevertheless, the analysis of flash flood activity in mountain environment still poses several scientific challenges, which are mainly related to the lack of systematic records (Stoffel et al., 2010). Long-term records of flash flood activity are often missing in remote environments, which in turn prevent the study of their impacts as well as a rational analysis of their drivers and ultimately meteorological triggers. On forested slopes, trees growing next to mountain streams can be used as a biological proxy and thus provide valuable proxy records to define the spatio-temporal patterns of past process activity with sometimes up to seasonal accuracy (Ballesteros-Cánovas et al., 2015a; Stoffel and Wilford, 2012; Stoffel et al., 2005, 2010, 2012). Intense flash flood events often cause damage to multiple trees (Ballesteros-Cánovas et al., 2015a; Sigafoos, 1964), which will respond with different growth disturbances, hereafter referred to as GD (Shroder, 1978; Stoffel and Corona, 2014). These GD have been widely used to reconstruct past activity of numerous hydrogeomorphic processes in different mountain ranges (see Ballesteros-Cánovas et al. (2015a); Stoffel et al. (2013) for a recent review), but such studies have generally focused on specific catchments (Astrade and Bégin, 1997; Ballesteros-Cánovas et al., 2011a,b, 2015b,c; Casteller et al., 2015; Ruiz-Villanueva et al., 2010; Šilhan, 2015; St. George and Nielsen, 2003; Stoffel et al., 2008; Zielonka et al., 2008), and have, with only a few exceptions, looked at the regional scale (i.e. Ballesteros-Cánovas et al., 2015c, in press; Bollschweiler and Stoffel, 2010; Procter et al., 2011; Schraml et al., 2015; Šilhan et al., 2015; Stoffel et al., 2014b). However, according to Procter et al. (2011), the regional assessment of past hydro-climate related processes could be of substantial help in terms of reducing lack of data and maximizing the information available in a given area. In addition, regional assessments allow for a better assessment of the complexity of the linkages between climate and flash floods at these scales (Ballesteros-Cánovas et al., 2015c; Glaser et al., 2010; Merz et al., 2014). Moreover, intra-catchment geomorphic and land-use comparisons are believed to yield insights into different and often varying hydrologic response of catchments (Blöschl, 2006; Costa, 1987; Glaser et al., 2010), which will in turn be useful for large-scale flash flood hazard delineations based on morphometric indexes (Fernández and Lutz, 2010; Guzzetti and Tonelli, 2004).

In this paper, we investigate and compare past flash flood activity in seven headwater catchments that exhibit considerable differences in forest cover and historical forest management in the Sierra de Guadarrama range (Spanish Central System). Based on a first series of data reported in a previous study (Ballesteros-Cánovas et al., 2015b) as well as highly resolved field data (i.e. LiDAR, aerial pictures, meteorological time series and forest management data), we analyze the role of geomorphic features and land use catchment predisposition on flash flood triggering. We also discuss hydro-meteorological causes of past events based on data from a nearby rain gauge, prior to focusing on the role and limitations of logging (or forest management history in other words) on the suitability of mountain forest catchments to be studied with dendrogeomorphic approaches.

2. Study site

The mountain catchments under investigation are located in the Guadarrama Mountain range (Spanish Central System; Fig. 1) which extends in a southwest to northeast direction for about 80 km, thereby dividing the Duero Basin (northwest) from the Tagus Basin (southeast). The range has a maximum altitude of 2428 m a.s.l. (Peñalara peak, Fig. 1). A total of seven adjoining catchments have been selected for this study, namely the Quebradas (QUE), Paular (PAU), Altozano (ATZ), Juncional (JUN), Cárcavas Del Valle (CV), Pintadas (PIN) and Valhondillo (VLH) streams. Moreover, we compare data reconstructed for these streams with results from existing dendrogeomorphic analyses of the adjacent Puentes (PU) and Majabarca (MJB) catchments (Ballesteros-Cánovas et al., 2015b).

With the exception of VLH, a tributary of Lozoya River (Tagus Basin), catchments considered in this study are tributaries of the Eresma River (Duero Basin) and located in the Montes de Valsaín (hereafter Valsaín Forest). All catchments are within the recently created Sierra de Guadarrama National Park.

As a result of the well-documented history of forest interventions since the late 18th century in the Valsaín Forest, detailed records exist on forest management interventions (Dones and Garrido, 2001) and for individual allotments (i.e. exploitation areas).

The catchments selected in this study generally have a NW orientation except for PAU catchment where the orientation is towards the W and for VLH catchment where water flows to the NE. Granitic and gneissic lithologies are dominant and determine a regular and rounded topography. The presence of gelifraction processes produces sufficient amounts of loose sediments which are then mobilized during intense hydro-geomorphic events. The distribution and orientation of the drainage network is associated with the local fault system with predominance of north-western features in the study area (Bullón, 1986; Pedraza et al., 2005). Arborescent vegetation at the study sites is formed primarily by *Pinus sylvestris* L., a species typical for subalpine altitudes (1600–2000 m a.s.l.) in the Guadarrama Mountain range (Ruiz del Castillo, 1976).

Climate in the area is defined as Mediterranean with continental influences which can be considered 'humid continental with warm summers' (type 'Dsb' according to the Köpper–Geiger classification, Peel et al., 2007). Average annual precipitation is 1223 mm with large amounts of rainfall typically in April and May as well as between October and January. Mean annual air temperature is 6.9 °C with monthly means ranging from 0.4 °C in January to 17 °C in July at the level of the meteorological station Navacerrada situated at 1894 m a.s.l. (AEMET, 2011). Results from the previous study (Ballesteros-Cánovas et al., 2015b) carried out in the PU and MJB catchments suggest that the rainfall thresholds triggering flash floods vary with the seasonality of events. Therefore, flash floods occurring in spring were typically released during events with lower rainfall totals than those triggered in autumn and winter, therefore suggesting an important role of snowmelt processes in the triggering of flash floods (Ballesteros-Cánovas et al., 2015b).

3. Material and methods

3.1. Dendrogeomorphic analysis

In this study we used standard dendrogeomorphic procedures to date past flash flood activity from trees, following the guidelines of Stoffel and Corona (2014). In a first step, field surveys were performed focusing on the detection of geomorphic features typically created by flash floods, such as lateral levees, terminal lobes as well as bank and/or terrace erosion. Based on this recognition, we sampled trees located in the transport-reaches of the fluvial systems and at locations where obvious interactions took place between the mobilized sediment and living trees. Only trees with visible signs of disturbance have been

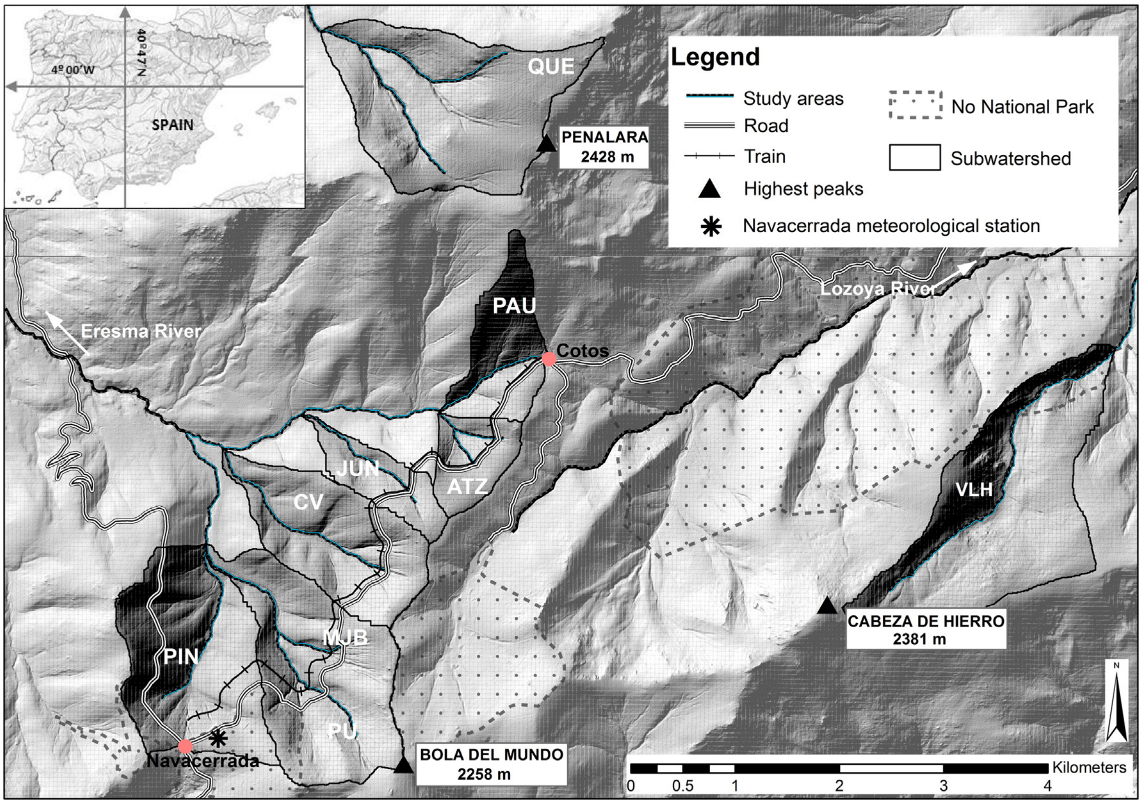

Fig. 1. Location of the study streams. Highlighted areas represent the study watersheds. Dotted polygons show areas which are not inside the National Park. Triangles mark the location of the highest peaks in the study area: Peñalara, Cabeza de Hierro and Bola del Mundo.

chosen, mostly in the form of impact scars. By contrast, trees with damage induced by anthropogenic interventions (forest management-logging) or natural processes other than flash floods (e.g., rock falls, soil creeping, fires and biological perturbations) have not been sampled and thus excluded from the analyses.

Disturbed trees were sampled using an increment borer (Grissino-Mayer, 2003). Scars on stems were analyzed at the contact between the scar edge and the intact wood tissue (Ballesteros-Cánovas et al., 2010; Schneuwly et al., 2009a,b) through the extraction of at least two samples. Increment cores were then prepared and measured using the standard dendrochronological procedures as described in Stoffel and Corona (2014). From each tree, growth series were measured visually checked for dating errors and then statistically cross-dated using an

Table 1
Sample characteristics and growth disturbances (GD) induced by past flash flood events. (*) Results of Majabarca and Puentes are from previous research (Ballesteros-Cánovas et al., 2015b). JUN stream did not show any injured tree in the field and was not therefore included in this table.

Catchment	Nb trees	Nb samples	Average age	Nb dated events (1813–2014)	GDs	
					Scars	Growth suppression
Quebradas	7	16	137 ± 25	6	8	8
Paular	12	19	111 ± 59	4	7	6
Altozano	5	16	150 ± 55	4	7	6
C. del Valle	6	9	122 ± 50	1	2	5
Pintadas	8	14	83 ± 27	2	4	4
Valhondillo	25	43	95 ± 30	7	6	17
∑ *Total new*	63	117	125 ± 25		34	46
Majabarca (*)	*14*	*70*	*149 ± 25*	*5*	*14*	*4*
Puentes (*)	*164*	*217*	*150 ± 77*	*19*	*77*	*186*
∑ *Total*	241	404			125	236

Table 2
Flash flood events dated in the study area, including those previously reported by Ballesteros-Cánovas et al. (2015b). * matched events between new and precedent reconstructions in the study area. ** new dated events in this paper. Boldface letter highlighted years with a special number of evidence and happened in three or more catchments.

Year	Evidences	No of streams	Site
1813	1	1	Puentes
1830	1	1	Puentes
1853	1	1	Puentes
1858	1	1	Puentes
1884	1	1	Puentes
1900	2	1	Puentes
1906	1	1	Puentes
1911**	1	1	Quebradas
1926*	3	2	Majabarca and Valhondillo
1933	3	1	Puentes
1935**	6	1	Valhondillo
1936*	**21**	**3**	**Quebradas, Valhondillo and Puentes**
1941**	2	2	Altozano and Quebradas
1945	3	1	Puentes
1947	3	1	Puentes
1950*	**4**	**3**	**Puentes, Majabarca and Valhondillo**
1952	7	1	Majabarca
1954*	13	2	Puentes and Valhondillo
1956	3	1	Puentes
1966*	**7**	**3**	**Majabarca, Puentes and Quebradas**
1973*	**3**	**3**	**Puentes, Quebradas and Valhondillo**
1984*	3	1	Puentes and Quebradas
1989**	2	1	Pintadas
1993**	3	2	Paular and Altozano
1995**	4	1	Paular and Altozano
1999*	**15**	**5**	**Majabarca, Puentes, Paular, Altozano and C. del Valle**
2004*	2	2	Puentes adn Paular
2005**	1	1	Pintadas
2008**	1	1	Altozano

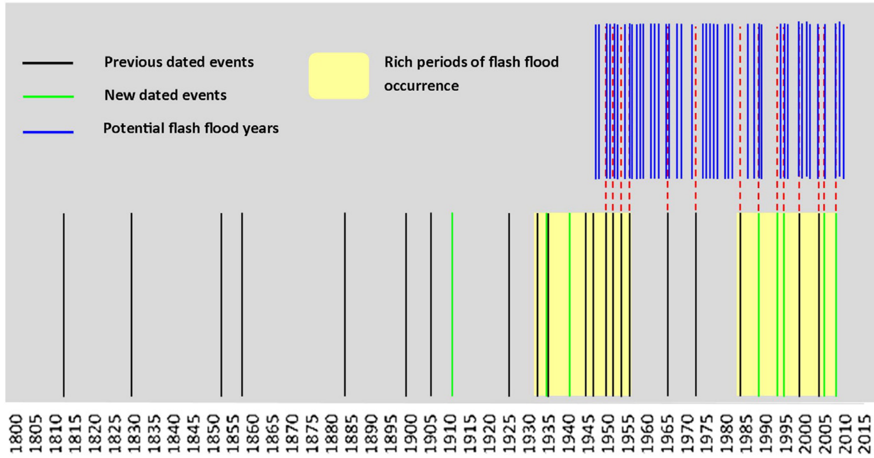

Fig. 2. Flash floods dated in the region between 1800 and 2014. Green lines show the new dated events in this study. Black lines represent the events reported by Ballesteros-Cánovas et al. (2015b). Yellow shadows highlight rich periods of occurrence: 1933–1956 and 1989–2008. And, related with the results in Section 4.4, the time line above is showing the 14 dated events (red dashed lines) using tree rings and the years in which the rainfall thresholds were exceeded one or more times (blue lines) since 1946.

existing reference chronology from the study area (Ballesteros-Cánovas et al., 2015b; Touchan et al., 2013). From the sampled trees the following characteristics have been considered reactions to flash flood activity and related scarring: callus tissues bordering scars as well as sudden growth suppression resulting from stem and/or root damage. Since *Pinus* spp. has a different genetic setup and does not generate tangential rows of resin ducts (or TRD; Stoffel, 2008) after mechanical damage, these species could not be used as a proxy to infer the seasonality of flash flood events (Stoffel and Beniston, 2006; Stoffel et al., 2008, 2011). Flash flood seasonality has instead been inferred from those samples showing wound borders on the increment rings and from a comparison between damage and meteorological record.

Definition of flash flood events was only based on scars and associated growth anomalies, whereas meteorological data has been used to narrow down the range of possible event dates by using the thresholds suggested by Ballesteros-Cánovas et al. (2015b); and references therein.

3.2. Catchment characteristics related with flash flood activity

GIS procedures were used to analyze catchment morphologies on the basis of hydrologically corrected 1-m and 5-m- Digital Elevation Models (DEMs) and by using the ArcHydro extension of ArcGis 10.0 (Tang and Liu, 2006). Data obtained via this approach was then used as the explanatory variable of differences in hydrological responses between the different catchments (Šilhan, 2014; Wilford et al., 2004). Parameters analyzed in this context include area, basin perimeter, slope, vertical relief as well as orientation. Additionally, four derived indexes were computed, namely:

1. *Melton index* (*Mr*): index of catchment propensity to the occurrence of debris flows, debris floods and flash floods. This parameter is calculated dividing the watershed relief by the square root of watershed area (Melton, 1957).
2. *Circulatory ratio* (*Cr*): ratio of basin area to the area of the circle having a perimeter equal to that of the drainage basin (Miller, 1953).
3. *Compactness constant* (*Cc*): ratio of the basin perimeter to the circumference of the circle having an equal area as the basin area (Horton, 1932).
   Both the *Cr* and *Cc* parameters describe the basin form and are related to the arrival time of wave flows to the basin outlet and, therefore, condition flow peak discharge.
4. *Concentration time* (*Ct*): time needed for water to flow from the most remote point in a watershed to the watershed outlet (Haan et al., 1994). This parameter is related to the longitude of the main channel and its average slope (MOPU, 1990).

In a next step we performed an intra-catchment comparison by testing the data for correlations between the basic and derived geomorphic parameters, the amount of wood extracted from the forests (explanatory variables) and the number of dated events (explained variable) in each catchment. This analysis has been carried out using Spearman's rho coefficient, which is one of the most commonly used indices in the case of low sample numbers (Sierra, 1988). The confidence level was set to 0.05 and 0.01, respectively.

Table 3
Morphometric parameters of catchments in the study site. Lower frame: average values of parameters for the whole of the study area (Vr: vertical relief; A: area; J: slope; Tc: time of concentration; Mr.: Melton ratio; Cc: compactness constant; Cr: circulatory ratio).

Basin	Torrent	Vr (m)	A (km^2)	J(°)	Tc (h)	Mr (10^3)	Cc	Cr	Orient
Eresma	Quebradas	812	2.86	15.5	0.16	0.28	1.62	0.38	W
	Paular	195	0.98	3.5	0.28	0.2	1.66	0.36	W
	Altozano	307	0.47	16.8	0.07	0.65	1.4	0.5	NW
	Juncional	499	0.6	15.1	0.12	0.83	1.93	0.26	NW
	C. del Valle	597	1.73	11.2	0.2	0.35	1.62	0.38	NW
	Majabarca	422	0.39	21.3	0.08	1.06	1.37	0.53	NW
	Puentes	760	1.48	16.1	0.23	0.51	1.51	0.43	NW
	Pintadas	589	2.3	10.8	0.17	0.25	1.52	0.42	NW
Lozoya	Valhondillo	793	3.02	9.2	0.15	0.26	1.76	0.32	NE
	Averages	552.7 ± 72.6	1.5 ± 0.3	13.3 ± 1.7	0.2 ± 0.02	0.5 ± 0.1	1.6 ± 0.06	0.4 ± 0.03	

Table 4
In bold, correlation factors (ρ) between the number of dated events and the geomorphic characteristics of the catchments, as well as with the extracted volume of wood in each catchment.

		Dated event	Melton ratio	Compactness constant	Circulatory ratio	Vertical relief	Area	Slope	Time of concentration	Extract.volume
Dated events	ρ	**1.000**								
	Sig. (bilateral)	**.**								
Melton ratio	ρ	**−.084**	1.000							
	Sig. (bilateral)	**.831**	.							
Compactness constant	ρ	**−.286**	−.393	1.000						
	Sig. (bilateral)	**.456**	.295	.						
Circulatory ratio	P	**.286**	.393	−1.000**	1.000					
	Sig. (bilateral)	**.456**	.295	.	.					
Vertical relief	ρ	**.460**	−.150	.209	−.209	1.000				
	Sig. (bilateral)	**.213**	.700	.589	.589	.				
Area	ρ	**.359**	−.683*	.452	−.452	.800**	1.000			
(forested)	Sig. (bilateral)	**.458**	.042	.222	.222	.010	.			
Slope	ρ	**.209**	.850**	−.736*	.736*	−.050	−.583	1.000		
	Sig. (bilateral)	**.589**	.004	.024	.024	.898	.099	.		
Time of concentration	ρ	**.100**	−.667*	.251	−.251	.150	.400	−.583	1.000	
	Sig. (bilateral)	**.797**	.050	.515	.515	.700	.286	.099	.	
Extracted volume	ρ	**−.231**	−.743*	.795*	−.795*	−.060	.491	−.922**	.587	1.000
	Sig. (bilateral)	**.337**	.035	.018	.018	.888	.217	.001	.126	.

* . The correlation is significant at 0.05 level (bilateral).
** . The correlation is significant at 0.01 level (bilateral).

Sediment availability was assessed during field surveys and by using aerial pictures. Analyses focused on the description of source areas of periglacial material in the upstream portions of the catchments and on old deposits from former flash-flood activity along the channels (i.e. lateral levees and terminal lobes).

3.3. Forest management

Historical records of forest management were used to quantify volumes of extracted wood in each catchment. Total volumes were then weighted according to the area of allotments within each catchment and confronted with the number of dated events. Furthermore, aerial imagery was used to estimate volumes of extracted wood from the floodplains of each channel. This estimation was made in an area of 10 m on either side of the streams, by using pairs of pictures of each catchment and for the periods 1956–1992, 1992–1997, 1997–2002, 2002–2004, 2004–2008, and 2008–2010, with the aim to see changes in vegetation close to the channels. These analyses seek to provide relative values of the influence of human interventions in forests as a controlling factor of the catchments' suitability to carry out dendrogeomorphic studies. This is because forest management can limit the existence of old, disturbed trees that form the essential basis of dendrogeomorphology.

3.4. Hydro-meteorological analysis

Hydro-meteorological records are based on daily data from the Navacerrada meteorological station (40° 47′N, 4° 00′W, 1894 m a.s.l.;

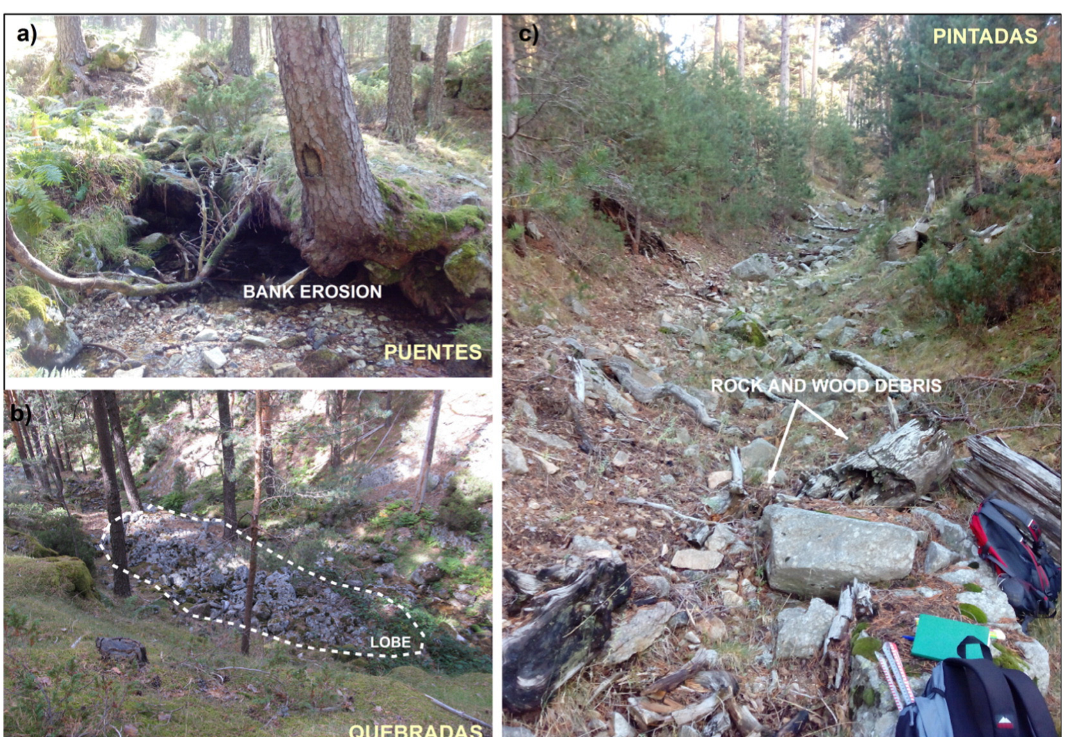

Fig. 3. Pictures showing different sediment sources from three torrents (PU, QUE, and PIN).

data available from 1946) have been screened to refine the (sub-) annually reconstructed dates of flash floods and to characterize them from the point of view of their climatic triggers. We assume here that flash floods are triggered by heavy and/or prolonged rainfall events (>30 mm), sometimes coupled with rain-on-snow processes (Ballesteros-Cánovas et al., 2015b). Consequently, the criteria used to analyze potential rainfall thresholds focused on the maximum 1-, 3-, 5-day accumulated liquid precipitation events (with air temperature >1 °C). In addition, we consulted flow series from the Eresma (station no 50 of the Hydrographic Confederation of the Duero basin, 1912–2007) and Lozoya (station no 3002 of the Hydrographic Confederation of Tagus basin, 1966–2012) gauging stations so as to compare the events dated with tree-ring series with the year or the season of flash floods and to possibly define the exact date of their occurrence with a daily temporal resolution.

Finally, based on previous studies (Ballesteros-Cánovas et al., 2015b) and defining 1-, 3- and 5-day rainfall thresholds triggering flash flood events, we performed a threshold exceedance analysis by season on the entire rainfall series, so as to analyze differences between days exceeding these thresholds and the number of dated events (1946–2013).

4. Results

4.1. Regional flash flood activity as derived from tree rings

A total of 117 samples (63 disturbed trees) have been sampled from seven catchments, with a majority of disturbed trees being found at VLH (40%; 25 trees and 43 samples). A much smaller number of suitable trees with disturbances were sampled at CV (9.5%; 6 trees and 9 samples).

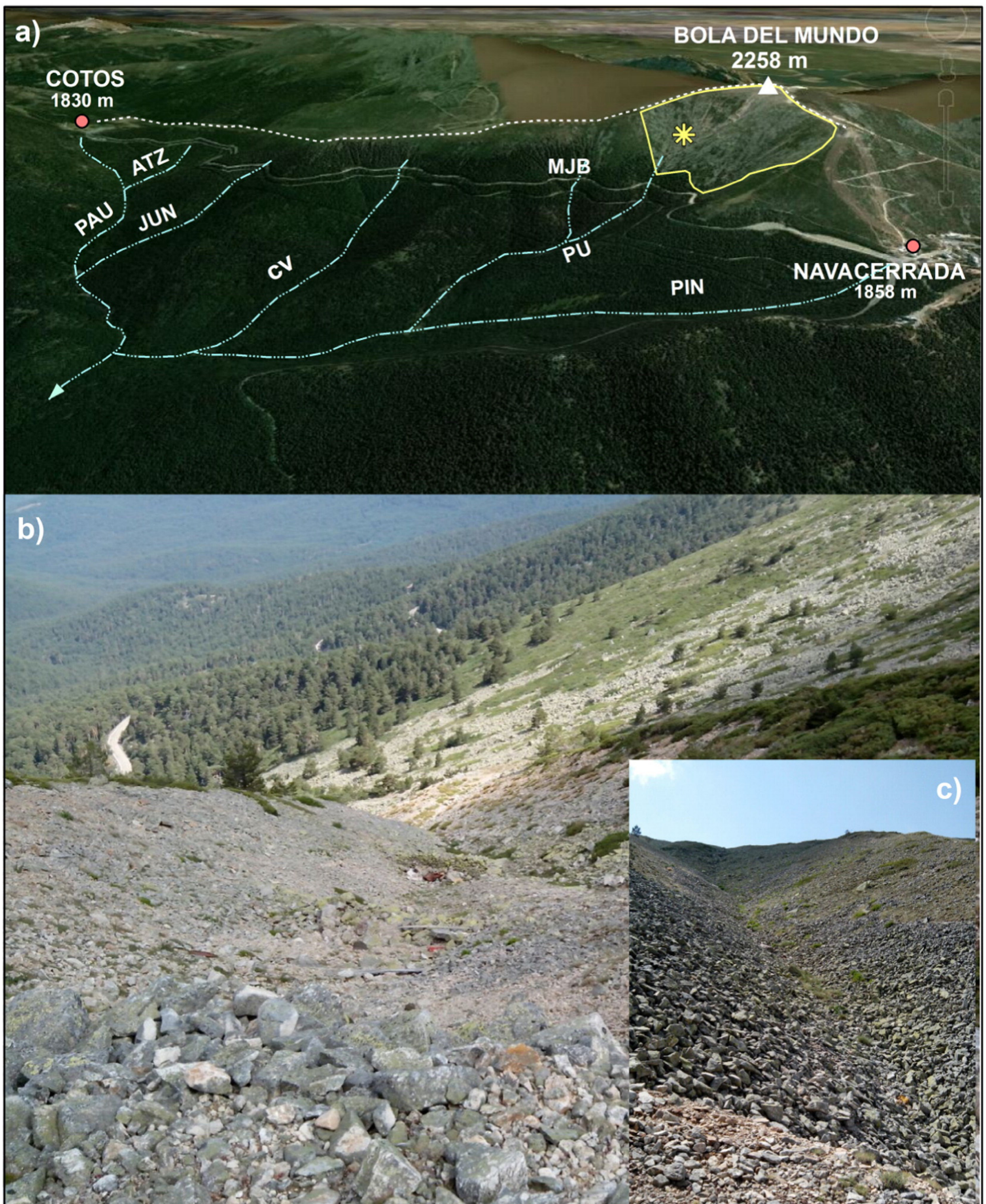

Fig. 4. View of the top of the Puentes stream. a) Situation in the study area. b), c) Pictures taken from the yellow-star showing the unconsolidated deposit and the pronounced slope steepness. The vegetation is sparse through to the start of the tree line.

The average age of disturbed trees was 125 ± 25 years. Older trees were observed at PU (average age of 150 ± 77 years), whereas the youngest disturbed trees were found at PIN (average age of 83 ± 27 years) (Table 1). Tree-ring analysis of disturbed trees resulted in 80 growth disturbances (GD; 34 scars and 46 growth suppressions) induced by past flash flood activity (Table 1). Among these, abrupt growth suppression was observed most frequently (58%), followed by impact scars (incl. presence of callus tissue; 42%).

Based on the GD analysis, we identify eight undocumented flash flood events covering most of the 20th and early 21st centuries, namely 1911, 1935, 1941, 1989, 1993, 1995, 2005, and 2008 (Table 2). The number of dated flash floods varies between catchments, as does the number of events occurring simultaneously in several catchments. In detail, we observe 7 events at VLH, 6 at QUE, 4 at PAU and ATZ, 2 at PIN, and one event at CV (Table 1). In most cases (59%), evidence of past flash floods can be found in just one catchment, with no or only limited simultaneous replication in other catchments (Table 2). The most replicated flash flood apparently occurred in 1999, with evidence for a large-scale, simultaneous event in at least five catchments (i.e. PAU, ATZ, CV, MJB, and PU). Furthermore, four flash flood events (i.e. 1936, 1950, 1966, and 1973) have affected at least three catchments (see Table 2).

The partial minimal occurrence at all study sites is at a higher level between 1933 and 1956 with at least 10 events in 23 years (0.39 events $yr.^{-1}$). Above-average occurrence in events is also observed in the period 1989–2008 with 8 events in 19 years (0.37 events $yr.^{-1}$) (Fig. 2).

4.2. Differences in natural catchment disposition to flash floods

Table 3 provides details on the morphometric characteristics of each catchment. The largest catchments analyzed here are VLH (3.02 km^2), QUE (2.86 km^2) and PIN (2.3 km^2), whereas the smallest catchments include MJB (0.39 km^2) and ATZ (0.47 km^2). Average slope and concentration time was 13.3 ± 1.7° and 0.2 ± 0.02 h, respectively. Based on morphometric indices, larger vertical relief (i.e. values above the average of 552.7 m) was observed at QUE (812 m), VLH (793 m), PU (760 m), CV (597 m) and PIN (589 m), whereas larger Melton and Circulatory ratios (with values above the average Mr. = 0.5 ± 0.1 and Cr = 0.4 ± 0.03, respectively) were obtained for MJB (1.06), JUN (0.83), ALT (0.65) as well as for MAJ (0.53), PU (0.43), and PIN (0.42) respectively. Based on these indexes, the PIN and PU catchments exhibit larger susceptibilities to trigger flash floods than the other catchments.

Correlations between dated flash flood events and catchment predisposition is shown in Table 4. Positive correlations were found between the number of dated events and vertical relief (0.46), circulatory ratio (0.28) and concentration time (0.1), whereas negative correlations were observed between the number of dated events and Melton index (−0.84) and extracted volume of wood (−0.23). All of the correlations given above were statistically significant (Sig. (bilateral) <0.01 and 0.05) with values ranging between 0.21 and 0.83.

Field surveys also revealed that sediment transported by flash floods mainly stems from channel banks (Fig. 3a) or old flash-flood deposits like levees or lobes (Fig. 3b). Field observations furthermore show that coarse sediment and woody debris remaining in the channel can be mobilized during events as well (Fig. 3c).

However, in the case of catchment PU, which is by far the most active catchment according to our analysis, unconsolidated material of periglacial origin (89 ha) yet forms another big source of sediment (yellow polygon in Fig. 4a) with important, quasi-permanent subsuperficial runoff.

4.3. Different suitability of catchments for dendrogeomorphic research

Analysis of the volumes of wood extracted from the catchments under investigation showed dissimilar patterns throughout the period covered (1940–2009; no data for VLH; Fig. 5).

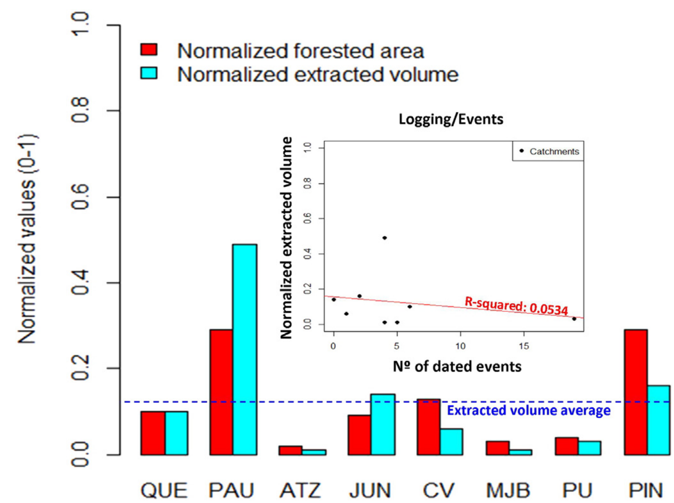

Fig. 5. Graphic representation of the relationship between the normalized values of forested area and wood extracted volume in each catchment with the events dated for these sites. Blue dashed line is representing the wood extracted volume average (0.13).

The total volume of extracted wood in all catchments was 179,438 m^3. Extraction was very different between catchments and most important in PAU with almost 87,950 m^3 (49% of the total volume), whereas the lowest amount was extracted in ATZ with only 1277 m^3 (1% of the total). In addition, the scatter plot in Fig. 5 clearly indicates a negative correlation ($\rho = -0.231$ and $R^2 = 0.0534$) between the number of dated events and the normalized volume of extracted wood in each catchment.

The existence of stumps near the current position of streams in the catchments (Fig. 6) and the comparison of vegetation cover evolution based on aerial photography also suggests that forest management works included areas close to the stream channels (Table 5).

Such work in the immediate vicinity of the channel network can be observed at PAU between 1997 and 2002 and 2004 and 2008; at JUN between 2002 and 2004; at CV between 1956 and 1992, and at PIN between 1997 and 2002 and 2004 and 2008. The most significant change in forest cover occurs in PIN between 1997 and 2002, when a large clearance becomes apparent next to the central segment of the study reach including the 10-m buffer on either side of the river (Fig. 7).

4.4. Rainfall analysis and comparison with dated events

The hydrometeorological characterization of the more recent reconstructed flash flood events (i.e. 1989, 1993, 1995, 2005, and 2008) is presented in Table 6.

The average 1-day rainfall precipitation totals recorded were 60.2 ± 5.1 mm; whereas the 3- and 5-day totals were 100.0 ± 3.0 mm and 123.3 ± 18.6 mm, respectively. The presumably largest rainfall over the period of observation potentially occurred at PIN on 19 November 1989 with a 1-day precipitation of 78.5 mm, 3-day totals of 172.9 mm and a 5-day sum of 236.1 mm. The unusual character of this rainfall event is also reflected in the extremely high monthly runoff in the Eresma River where 16.07 Hm^3 has been recorded, which corresponds to 19% of the river's annual contribution (88.2 Hm3). The 1-day rainfall sums of the events in 1993, 1995, 2005, and 2008 did not differ significantly from the 1989 event with 66.7, 65.8, 66.4 and 69.3 mm of rainfall, respectively. However, the 3- and 5-day totals have been substantially smaller during these events with values ranging from 114.5 to 66.4 mm and 130.1 to 66.4 mm. Based on the seasonality of scars within the tree rings and the occurrence of heavy rainfalls in the area, fall (November 1989, October 1993, November 1995, October 2005) appears to be the most likely seasons for flash flood occurrences, whereas only one event was attributed to spring (April 2008).

Analyses of the daily precipitation records since 1946 showed that the 1-, 3- and 5-day rainfall thresholds (Fig. 8) were exceeded

Fig. 6. Picture taken in QUE torrent, providing an example of the generalized harvesting activity in the study areas. Yellow stars indicate stumps close to the channel. White dotted lines highlight the out-wood path. The tree in the image is a good example of a tree not suited for dendrogeomorphologic analyses. This is because, despite its proximity to the stream, the tree ring record of this tree possibly exhibit noise related to several causes: 1) logging of its immediate neighbours may result in a strong increment in the growth of the tree-rings; 2) the logging trees removed through the out-wood path and the equipment used for this purpose can damage this tree leaving signals similar to the ones left by flash flood activity; 3) The rocks impacting the stem probably come from the cleaning of the out-wood path, thus leading to possibly erroneous interpretations about it origin.

52.3 ± 17.2, 35.7 ± 18.4 and 34.3 ± 19.2 times, respectively (Table 7).

By contrast, 14 of the events dated in this study represent 20% of the years covered by the period for which gauging records exist (Fig. 2). In this respect, the analysis also shows that the threshold was more frequently exceeded in fall (70.0 ± 7.8 times) and spring (43.3 ± 15.2 times) than in winter (9.0 ± 1.7 times) (Table 7). A more detailed assessment shows that the months of April (58 times), May (59 times), October (84 times), and November (69 times) were those months with the largest number of exceedances.

5. Discussion and conclusions

In this paper we report on the analysis of 117 tree-ring samples taken from 63 trees affected by past flash flood activity in seven different mountain catchments of the Guadarrama Mountain Range of the Spanish Central System. Our regional reconstruction provides insights into eight previously unknown flash flood events in the region and thus complements the data recently presented by Ballesteros-Cánovas et al. (2015b) for two specific catchments in the same area. Therefore, this study demonstrates along with other assessments (Ballesteros-Cánovas et al., 2015c, in press; Procter et al., 2011; Šilhan, 2015) that regional approaches, rather than individual catchment analyses, can improve the flash flood reconstruction. Our analysis also provides a basis for intra-catchment comparisons based on differences in geomorphic and land-use predisposition, thus conditioning suitability to record past flash floods based on disturbed trees. Likewise a hydrometeorological characterization of rainfall, gauging thresholds and event seasonality has been carries out.

Table 5
Results for the existence of logging inside the 10 m-buffers of the streams. *no information, **no logging, ***logging. Only in six pairs of pictures was it possible to see variations in the vegetation close to the rivers. This does not imply that these are the only areas affected by logging, but they are the most evident ones.

		1956–1992	1992–1997	1997–2002	2002–2004	2004–2008	2008–2010
QUE	Vol (m^3)	18,747*	970*	445*	688*	0*	0*
PAU	Vol (m^3)	43,332*	5773*	6522***	674**	11,577***	2180*
ATZ	Vol (m^3)	7215**	3464**	287**	129**	4529**	1889*
JUN	Vol (m^3)	26,270**	3204**	784 **	217***	8880**	694*
CV	Vol (m^3)	28,997***	2459**	8025***	3634**	409**	0*
MJB	Vol (m^3)	8474**	2723**	293**	56**	677**	0*
PU	Vol (m^3)	31,661 **	1352**	4354**	511**	3460**	54**
PIN	Vol (m^3)	51,190**	2302**	5189***	554**	5061***	70*

The flash flood reconstruction obtained in this study has been conditioned by the low number of reliable disturbed trees observed in each of the catchments. Therefore, the sampling strategy followed was extremely selective and exclusively focused on reliable trees with clear signs of visible scars in the flow direction of flash floods (Stoffel and Corona, 2014). We therefore clearly avoided any other signs and/or less conclusive dendrogeomorphic evidence (e.g., tilted trees, decapitated trees) or the sampling of trees located in the vicinity of existing trekking paths or too far away from the present-day stream. The strict selection of trees was also clearly motivated by the traditional use of

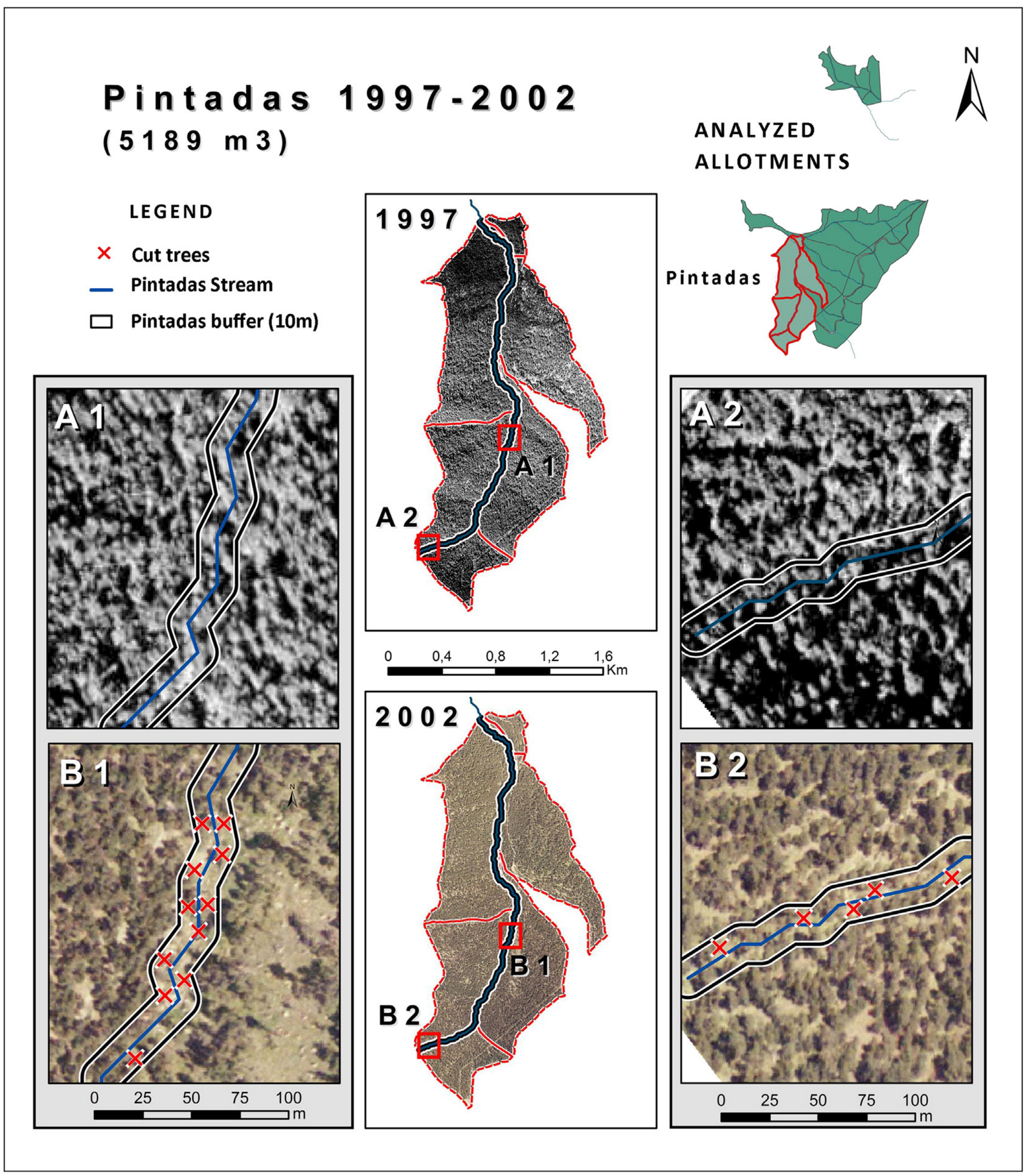

Fig. 7. These pictures are an example from the PIN catchment showing the variation of the vegetation between 1997 and 2002. During this time lapse, 5189 m^3 of wood was extracted from the PIN allotments cantons. A large space without trees appears in the middle part of the torrent in 2002 (boxes A1 and B1). These harvesting works were extended to the river and several trees from the buffer area were cut down (red crosses).

Table 6
Precipitation records (1-, 3-, and 5- day totals) and hydrological information from two gauged stations in Eresma and Lozoya rivers, associated with dated flash flood events. * highlight other possible dates based on precipitation and gauging data. (mo. avg.: monthly average; Qic: maximum instantaneous flow; Qavd: daily average flow).

Year	Date	Site	Precipitation (mm)			Flow discharge	
			1-Day	3-Day	5-Day	Eresma River	Lozoya River
1989	19.nov	PIN	78.5	172.9	236.1	Monthly contribution $=16.07$ Hm^3 (mo. avg. $=8.24$ Hm^3) (annual contribution $=88.2$ Hm^3)	$Q_{avd}=8.24$ m^3/s (mo. avg. $=1.74$ m^3/s)
	17.déc*		33	79.4	102.5	Monthly contribution $=37.91$ Hm^3 (mo. avg. $=12.96$ Hm^3) (annual contribution $=88.2$ Hm^3) $Q_{ci}=40.2$ m^3/s (month average $=35.8$ m^3/s)	$Q_{avd}=11.5$ m^3/s (mo. avg. $=1.87$ m^3/s)
	11.oct		66.7	106	130.1	Monthly contribution $=7.74$ Hm^3 (mo. avg. $=3.14$ Hm^3) (annual contribution $=127$ Hm^3)	$Q_{avd}=2.65$ m^3/s (mo. avg. $=0.77$ m^3/s)
1993	16.oct*	PAU and ATZ	48.8	67.1	129.1	Monthly contribution $=7.74$ Hm^3 (mo. avg. $=3.14$ Hm^3) (annual contribution $=127$ Hm^3)	$Q_{avd}=7.0$ m^3/s (mo. avg. $=0.77$ m^3/s)
	03.nov*		52.7	121.5	136.1	Monthly contribution $=18.89$ Hm^3 (mo. avg. $=8.24$ Hm^3) (annual contribution $=127$ Hm^3)	$Q_{avd}=17.77$ m^3/s (mo. avg. $=1.74$ m^3/s)
1995	10.nov	PAU and ATZ	65.8	71.8	71.8	Monthly contribution $=0.81$ Hm^3 (mo. avg. $=8.24$ Hm^3) (annual contribution $=141$ Hm^3)	$Q_{avd}=0.28$ m^3/s (mo. avg. $=1.74$ m^3/s)
2005	27.oct	PIN	66.4	66.4	66.4	Monthly contribution $=0.85$ Hm^3 (mo. avg. $=3.14$ Hm^3) (annual contribution $=66.8$ Hm^3)	$Q_{avd}=0.09$ m^3/s (mo. avg. $=0.77$ m^3/s)
2008	9-Avr	ATZ	69.3	114.5	114.5	No data	$Q_{avd}=2.5$ m^3/s (mo.avg. $=2.44$ m^3/s)
		Average	60.2 ± 5.1	89.5 ± 9.0	123.3 ± 18.6		

the forest and intense human pressure in terms of logging (Dones and Garrido, 2001; Tornero-Gómez, 2005). However, and despite the fact that we used a comparably small number of samples, evidence of reconstructed flash flood events tends to be very synchronous between catchments (i.e. 1926, 1936, 1941, 1950, 1954, 1966, 1973, 1984, 1993, 1995, 1999, and 2004) and also matches well with previous reconstructions and historical archives, as well as records of intense rainfall events.

In this sense, the observed evidence of nine flash flood events (i.e. 1926, 1936, 1950, 1954, 1966, 1973, 1984, 1999, and 2004) not only matches well with those reconstructed in MJB and PU catchments (Ballesteros-Cánovas et al., 2015a). Furthermore, we also recognize that some of the flash flood events (i.e. 1936, 1966, 1973, 1999, and 2005) seen in this study were previously defined in the nearby Sierra de Gredos catchment using dendrogeomorphic techniques (Ballesteros-Cánovas et al., 2010, 2011a,b; Ruiz-Villanueva et al., 2010) as well as described by different researchers and in archives (Benito et al., 2003; Díez Herrero et al., 2008; Morales and Ortega, 2002; Potenciano, 2004). Our results suggest, moreover, the occurrence

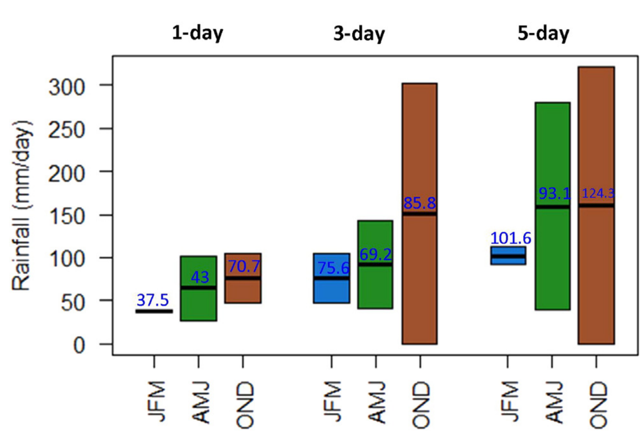

Fig. 8. 1-day, 3-day and 5-day average rainfall thresholds during reconstructed events and according to season. Values are based on a previous study (Ballesteros-Cánovas et al., 2015a) and the 1-, 3- and 5-day rainfall thresholds which have triggered flash floods are defined here. (JFM: January, February, March; AMJ: April, May, June; OND: October, November, December).

of at least eight flash flood events which would not have been recorded previously in the area (i.e. 1911, 1935, 1941, 1989, 1993, 1995, 2005, and 2008), although in three cases, 1989, 1993 and 2005, they have been detected in the Sierra de Gredos (Ballesteros-Cánovas et al., 2010, 2011a; Ruiz-Villanueva et al., 2010). The 2008 event was, moreover, weakly (Wit <0.5) identified in MJB and PU (Ballesteros-Cánovas et al., 2015b).

The hydrometeorological analysis has shown that most of the reconstructed events likely occurred in the fall (1989, 1993, 1995, and 2005) and that only one flash flood (2008) was triggered by spring rainfalls, a finding which is consistent with results of previous research in the wider study area (Ballesteros-Cánovas et al., 2015b; Ruiz-Villanueva et al., 2013).

This match between our reconstructions and data from other sources not only points to a common regional flash flood mode but also indicates that the contribution of our reconstruction may be considered significant, despite the fact that it was based on a relatively small number of samples, mainly because of the careful selection of high-quality samples (i.e. scars) and the fact that it was undertaken at the regional level. This assumption is well supported by the example of the study conducted at PU (Ballesteros-Cánovas et al., 2015b) where the 2008 event could not be found in a large number of samples as a result of differing event-definition criteria and the fact that the study only focused on the PU and ATZ catchments. This observation underlines that the quality of samples together with the event-definition criteria should be much more important than the overall number of samples taken in the field. Our findings are in line with those obtained by Stoffel and Bollschweiler (2009), who proved that a small number of samples may be used to characterize a minimum event frequency, although

Table 7
Number and averages of times exceeding the rainfall thresholds since 1946 to 2013.

	Winter	Spring	Fall	Average/threshold
1-Day	16	71	70	52.3 ± 17.2
3-Day	7	30	70	35.7 ± 18.4
5-Day	4	29	70	34.3 ± 19.2
Average/season	9.0 ± 1.7	43.3 ± 15.2	70.0 ± 7.8	

the authors also recognize that reliable conclusions can only hardly be drawn in this case.

As for the dating of flash flood events, one needs to distinguish between the occurrence of such events in each catchment and their reconstruction. From the data, we speculate that the occurrence is related to the specific local geomorphic and climatic settings of each catchment. In this respect, our results suggest that the most influential parameter in the occurrence of flash flood events is the vertical relief (Vr, $\rho = 0.46$), even if correlation in this case was not seen to be statistically significant (Sig. (bilateral): $0.21 > 0.01$ and 0.05) in this case. In similar studies undertaken outside the Iberian Peninsula, clear correlations have been reported between basin morphometry and flash flood frequency (Šilhan, 2015). To explain the lack of correlation in the Sierra de Guadarrama mountain range, we believe that the capacity of a catchment to deliver unconsolidated material during events – which is in addition capable of damaging existing trees – is the key, but this element never appears explicitly among the geomorphic parameters used in our discipline. Blöschl et al. (2015), Borga et al. (2014) and Marchi et al. (2009), for instance, emphasized that soil characteristics, such as hydraulic conditions, saturation and infiltration, play an important role in the activation of rapid runoff which can eventually become prevailing transfer processes. The upper part of the PU catchment, where large flash flood activity has been observed, is in fact characterized by extensive deposits of unconsolidated material (i.e., fine-grained rock and soil debris from periglacial activity) occupying steep slopes void of vegetation (Fig. 3). Such conditions will, in fact, favor subsuperficial runoff, especially in combination with snowmelt processes, thereby also increasing the possibility for debris to be mobilized (Costa, 1984). Specifically, Blöschl et al. (2015), remark that the occurrence of river floods triggered by rainfall and snowmelt are also related with processes occurring at atmospheric and river system (i.e. flood wave propagation and superposition of flood waves) levels. They assume that any change along the time in these processes will also lead to changes in the floods. In this study, we are working with changes at spatial level between catchments and here we assume no differences in the atmosphere and river system characteristics between catchments.

The fact that our reconstruction only contains 20% of the years for which rainfall events exceeded the defined 1-, 3-, and 5-day rainfall thresholds may be due to (i) the fact that a flood that is triggered not only depends on rainfall, but also on the temporary state of a catchment and its processes (Blöschl et al., 2015); or (ii) an incomplete reconstruction of past flash flood events and to certain limitations of dendrogeomorphology in providing a complete record of past events (see Stoffel and Bollschweiler (2008, 2009); Ruiz-Villanueva et al. (2010)). The assumed incompleteness of the record could be related to (i) the generalization of climatic conditions which was assumed for all catchments; (ii) the fact that only total daily rainfall sums were considered, and not precipitation intensity, due to the absence of such records, being well aware that these could have played an important role in flash flood occurrence (Quevauviller, 2014); or to (iii) the fact that the areas located next to the channels have been influenced quite heavily by forest management interventions during the last century, thus compromising the catchments' suitability for more specific dendrogeomorphic studies. In this context dendrogeomorphic catchment suitability refers to forest characteristics, namely that (i) the trees are sufficiently old; (ii) they have not been cleared; and (iii) that they have recorded flash flood events. Obviously, catchments with more trees meeting these conditions would be even more suited to carry out dendrogeomorphic studies. Thus we hypothesize that land-use changes in relation with intense logging over the last decade may have substantially reduced the amount of proxy evidence of flash floods in several catchments. In this sense, our results represent a minimum frequency assessment. The negative correlation between dated events and extracted wood volume ($\rho = -0.231$, scatter plot in Fig. 5) can be seen in the general context between deforestation, runoff increment and extreme flash flood events occurrence (Sanyal et al., 2014; De la Paix et al., 2013; among others). However, the cause of the increment of events (intense logging) is the same which complicates their detection, so it is not possible to draw any conclusions concerning the increment of events where logging has occurred based only on dendrogeomorphic studies.

It can nevertheless be concluded here that dendrogeomorphic techniques have substantially improved our knowledge of regional and local flash flood activity and their triggers, but that the number of reconstructed events is in fact biased by intense forest management interventions. As such, the number of reconstructed events reported in this study has to be seen as a minimum observed occurrence of events and cannot be considered an exhaustive record of past flash flood activity. Nonetheless, and despite the limited number of samples taken in the field, dendrogeomorphology has substantially complemented existing records and added evidence of eight new events which will be of help to improve the assessments of the local frequency and magnitude of floods at the catchment scale.

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