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Multidisciplinary study of flash floods in the Caldera de Taburiente National Park (Canary Islands, Spain)

M. Génova [a,*], P. Máyer [b], J. Ballesteros-Cánovas [c,d], J.M. Rubiales [a], M.A. Saz [e], A. Díez-Herrero [f]

[a] Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingeniería de Montes, Forestal y del Medio Natural, 28040 Madrid, Spain
[b] Universidad de Las Palmas de Gran Canaria, Departamento de Geografía, C/Pérez del Toro, 1, 35003 Las Palmas de Gran Canaria, Spain
[c] Dendrolab.ch, Institute of Geological Sciences, University of Berne, 3012 Berne, Switzerland
[d] Climatic Change and Climate Impacts, Institute for Environmental Sciences, University of Geneva, 1227 Carouge, Switzerland
[e] Departamento de Geografía y Ordenación del Territorio, Área de Análisis Geográfico Regional, Instituto Universitario de Ciencias Ambientales, Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain
[f] Geological Hazards Division, Geological Survey of Spain (IGME), E-28003 Madrid, Spain

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ABSTRACT

The national parks of the Canary Islands have specific environmental features that attract thousands of tourists every year. Most of the parks are located in mountainous areas, where hydrogeomorphic processes and their related hazards are frequent. The main aim of this study is to improve our understanding of the effects and frequency of these processes in an ungauged river basin located on the island of La Palma. In this river basin, the use of hydrological and hydraulic modelling based on classic data sources and flood risk analysis methods has important shortcomings because of a lack of or incomplete information. Here, we use palaeohydrological data from tree-ring analyses of disturbed trees as these appear to be the only reliable alternative. In addition, dendrogeomorphological data are compared with available meteorological and documental information to develop a multidisciplinary flash flood record. This is the first time that *Pinus canariensis* has been used in a dendrogeomorphological study we assess its suitability for the reconstruction of flash flood events. Such techniques have not been applied before in subtropical, tropical or equatorial areas. Tree-ring dating data were mostly obtained from 63 wounds from 54 trees from which two main types of post-damage tree response were identified: growth release and growth suppression. Injuries occurring in 1962 were especially relevant (affecting almost all the older trees) and also in 1997, with both presenting a large number of replications. Other injuries occurred in 1993, 2001, 2003, 2007 and 2009, obtaining a record from the dendrogeomorphological evidence. The data were compared with daily meteorological data and available documental sources in order to establish the most complete flash flood record possible. Our findings provide new insight into past flood events, their frequency–magnitude relationships, and climatic triggers, that can provide park managers with tools to reduce natural risks and their effects on visitors and infrastructure.

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1. Introduction

National parks (NPs) in the Canary Islands (Spain) are characterized by specific environmental features that attract thousands of tourists every year. These NPs are located, in most cases, in mountainous areas and are very rich in biodiversity and have many geological and geomorphological features, with consequent frequent hydrogeomorphic events that pose natural hazards. This makes it essential to carry out sustainable planning in order to accommodate the natural dynamics of the hydrogeomorphic processes with relevant financial and societal interests. The case of the Caldera de Taburiente NP on the island of La Palma is especially interesting, because historically it has suffered severe recurrent problems associated with catastrophic geomorphic events resulting in casualties and financial loss. In particular, Las Angustias gorge is frequently visited but flash floods have caused recurrent evacuations of visitors with occasional casualties (Arranz, 2006). Furthermore, the re-vegetation of the torrential floodplain and banks has been hampered by torrential floods, with losses of over €0.7 million in 2011 and 2012 (Díez-Herrero et al., 2012).

The high occurrence of flash flood events is a consequence of the geographical location of the Canary Islands that means exposure to Atlantic fronts; high slope susceptibility to mass-movement dynamics in the Taburiente (Colmenero et al, 2012; Máyer and Marzol, 2012); and rapid snowmelt from abrupt temperature fluctuations. The flash floods are characterized by sudden high discharges with significant sediment transport rates and high flow velocities (Mintegui and Robredo, 2008), which limits the ability of the research community to provide

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* Corresponding author.
E-mail addresses: mar.genova@upm.es (M. Génova), pmayer@dgeo.ulpgc.es (P. Máyer), juan.ballesteros@dendrolab.ch (J. Ballesteros-Cánovas), jm.rubiales@upm.es (J.M. Rubiales), masaz@unizar.es (M.A. Saz), andres.diez@igme.es (A. Díez-Herrero).

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timely warnings (Borga et al., 2011) and, together with the philosophy of non-intervention in NP that implies avoiding wherever possible the implementation of structural measures, makes territorial planning based on hazard definition the only way to safeguard the population from flood risk (Olcina, 2007; Schneuwly-Bollschweiler and Stoffel, 2013). However, although recent information on flash flood occurrence is recorded in national and regional media (e.g. December 1991, October 1997, November 2001), the frequency/magnitude estimates and total event impact are still unknown. Hydrological modelling and hydraulic modelling based on classic data sources and flood risk analysis methods have important shortcomings as a result of the lack of information about the Las Angustias basin (i.e., non-statistical representativity of precipitation and flow time series data; Thorndycraft and Benito, 2006), which may lead to unreliable results for this case study.

As a non-systematic palaeohydrological data source, a dendrogeomorphological approach using analysis of tree-rings from disturbed trees is a reliable alternative (Stoffel et al., 2010). This approach is based on the "process-event-response" concept proposed by Schroder (1980). From this point of view, trees may react with a specific physiological response at growth level to damage provoked by an event (e.g., cambial damage, tree burial, root exposure, changes in competition caused by geomorphic processes such as floods, rockfalls, snow avalanches, and erosion).

Early dendrogeomorphological studies of the relationship between tree-rings and geomorphological processes date from the 1960s (La Marche, 1963), but it was not until a few years later that the first publications appeared using this term (Alestalo, 1971). The application of dendrogeomorphological analyses to torrent dynamic related events such as debris flows and flash floods dates back to the same time. The earliest papers on these applications also date from the 1960s (Sigafoos, 1964; Harrison and Ried, 1967; see Ballesteros-Cánovas et al., in press), but it was not until the 1980s that these became standard, with the papers by Yanosky (1982a, 1982b, 1983, 1984), Hupp (1984, 1987, 1988), Hupp et al. (1987), McCord (1990), and Gottesfeld (1996). Since then, these techniques and data sources have become more widely used, although largely limited in geographical terms to North America and Europe (see compilation and distribution maps in Benito and Díez-Herrero, 2015).

In recent years, research experience has demonstrated that dendrogeomorphology is a very valuable tool for dating and quantifying various geomorphic processes, offering annual (or occasionally seasonal) accuracy (Stoffel et al., 2010) and high spatial representativeness (Corona et al., 2012). More specifically, in the context of flood/hydrogeomorphic processes, tree rings have been used to (i) build chronologies of events (e.g., Bollschweiler et al., 2008; Ruiz-Villanueva et al., 2010; Zielonka et al., 2008), (ii) analyse specific extreme events (e.g. Ballesteros et al., 2010), and (iii) quantify their magnitude, in both fluvial and torrential environments (e.g., Ballesteros et al., 2011; Yanosky and Jarrett, 2002) and have been successfully included in risk assessment reports (e.g., Ballesteros et al., 2013).

A case study is presented here reconstructing flash flood activity based on a dendrogeomorphological analysis of *Pinus canariensis* specimens affected by the impact of sediment load and woody debris during flood events. This reconstruction is based on 54 trees located at the head of the Las Angustias gorge (Caldera de Taburiente NP). The main aim is to improve our understanding of hydrogeomorphic processes in an ungauged NP river basin combining a dendrogeomorphological approach with meteorological and documental analyses that comprise a multidisciplinary record. The results provide new insights into past events and their climatic triggers which can be used by NP managers to improve hazard and risk assessment, and thus these research findings have implications for human safety.

2. Study area

The Caldera de Taburiente NP is located on La Palma, one of the western islands in the Canary archipelago (Spain), in the eastern central Atlantic Ocean (Fig. 1). The park is in the central-northern part of the island with an area of 47 km^2 and altitudes ranging from 2426 m asl. to the coastline (only to 700 m asl. inside the NP). This natural area was declared a national park in 1954. The NP is part of a magnificent volcanic relief, the result of the superposition of several volcanic edifices, with a large depression (Caldera), even though this final landform is not of volcanic origin (Carracedo et al., 2001).

This volcanic domed morphology was thus first eroded by a large mega-landslide that formed the central depression and some brechoid deposits inside it; and later it was incised to 300 m below the depression bottom by a dense network of gorges and canyons, with steep bedrock river reaches (waterfalls and rapids) and alluvial reaches (boulder and gravel braided rivers). Overall, three sedimentary Quaternary environments have been defined related to the geological evolution of the Taburiente and Cumbre Nueva complexes (Vegas et al., 1999): (i) a lacustrine setting for the Caldera de Taburiente epiclastic deposits; (ii) a fan delta that prograded from the mouth of Taburiente into the Atlantic Ocean; and (iii) a fan delta in lacustrine setting in the Cumbre Nueva palaeo-caldera.

The climate is subtropical, with mean annual temperatures of approximately 15 °C and relatively dry summers. The location of the Caldera, open to the west, is favourable to the arrival of Atlantic fronts and atmospheric disturbances and implies irregularly distributed precipitation values of about 1000 mm per year which are relatively high if compared with other areas of the archipelago. Commonly 75% of the annual rainfall is concentrated in winter and autumn. A more detailed analysis of precipitation based on the available meteorological stations is found in the Results section of this manuscript. Flash flood events derived from these precipitation patterns occur in these streams after heavy rains caused by Atlantic fronts (Fig. 2). Most of these flood events are a space-time evolution of several types of movements, ranging from landslides and rock avalanches (on cliffs and hillslopes) to debris flows, hyperconcentrated flows, debris floods and flash floods (Castillo, 2004).

Most of the hillslopes of the park are covered by forests mainly formed of *P. canariensis*, a Canary palaeoendemic species that grows in well preserved forests on this island (Arévalo and Fernández-Palacios, 2009). The forests extend up to 1800 m asl., and sometimes include willows (*Salix canariensis*) at the edges of ravines. Willows are generally related to the river bed and develop short-lived trunks that can be translocated and dragged with flood events (Fig. 3). In contrast, pines are able to survive low-to-moderate damage, producing characteristic growth patterns that allow tree ring dating of such disturbances. *P. canariensis* has unique characteristics among pines that are generally linked to the volcanic environments where it currently lives (Navascués et al., 2006). These include its colossal size, thick bark, resprouting ability, a characteristic heartwood, powerful taproot and high longevity (Climent et al., 2004; Esteban et al., 2005; Genova and Santana, 2006). These life-history traits make this species appropriate for tree ring studies to reconstruct geomorphic events by using dendrogeomorphological evidence (Díez-Herrero et al., 2013b).

This case study focuses on the Playa de Taburiente, a 2 km long Y-shaped stream reach located in the central part of the NP. It is formed by the confluence of two gorges (Verduras de Alfonso and Cantos de Turugumay) and the Taburiente river. This area is formed by an elongated alluvial filling of large boulders, boulders and gravel (Fig. 2). The river pattern and its deposits form a Donjek type gravel braided system where the hillslopes play an important role (rockfalls and debris flows). This area is one of the points in the park with most visitor transit, with three main trekking trails, proximity to the only camping site of the Caldera, a park services centre and a guide base.

Systematic flow data is not available, since the only gauge on the main river records only ordinary flow rates or low magnitude floods. This means that there is no systematic flow rate series available and also that it is impossible to calibrate and validate conventional precipitation-runoff models and therefore impossible to complete a common flood frequency analysis.

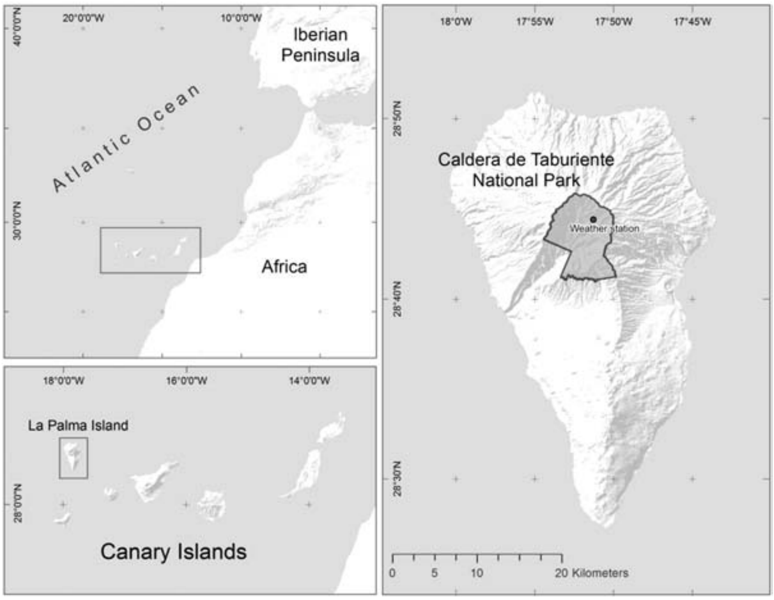


Fig. 1. Map showing positions of the island of La Palma, the Caldera de Taburiente National Park and the weather station.

3. Material and methods

To carry out the abovementioned study, simultaneous and complementary analysis and synthesis based methodological approaches are adopted, with a sequential combination of field data acquisition methods, in-laboratory study protocols, and desk-based processing and analysis methods (Fig. 4).

3.1. Sampling, dendrochronological analysis and dating injuries

Fieldwork was carried out during 2011–2013. In the field, all the disturbed *P. canariensis* (i.e., those presenting scars, exposed roots, resprouting or apical bud loss and dead trees, Fig. 5) were sampled following Zielonka et al. (2008). Furthermore, 16 undisturbed trees were sampled to provide a reference chronology according to Stoffel et al. (2010). A total of 270 samples were collected in the field: 233 from the 60 disturbed trees and 37 from the 16 undisturbed reference trees.

In some cases, trees showed several wounds corresponding to different events but more often only one impact signal per tree was observed. Other nearby trees with no visible injuries were also sampled, as scars may have already closed if they are old or not very wide.

Two or more increment cores (up to ten in some cases) were taken with an increment borer at breast height (approximately 1.30 m above the ground), or near the tree base if the scar was close to the ground. At least one core was taken in the non-affected tissue and one or more cores were extracted successively closer to the edge of the scar, until one core intersected the scar edge, or showed a distinctive growth pattern to identify the year when the scar was produced (Ballesteros et al., 2010). In addition, some wedges were taken from the overgrowing callus with a handsaw and whole sections were cut from two dead trees. Thus, 60 trees likely affected by floods were sampled. Each sampled tree was recorded in a spatial database with additional information including: (i) scar size and other evidence of disturbance, (ii) tree height and tree diameter at breast height (DBH) and (iii) sketches, drawings and photographs.

Once the samples had been dried and prepared, rings were measured (with accuracy 1/100 mm) using the Lintab measuring system and associated Tsap software (Rinn, 2003). For the cross sections or wedges, a minimum of four radius measurements per sample were made (Fig. 6a).

Tree ring growth series of disturbed trees were crossdated within each tree using classical methods including visual, graphic and statistical techniques (Cook and Kairiukstis, 1990) and checked using Cofecha software (Grissino-Mayer, 2001). Then, trees clustered by age and location (Fig. 7) were crossdated, preferably comparing the part of the series before disturbance.

Fig. 2. View of the valley bottom of the Taburiente river gorge (left) and the same reach during a flash flood in 2009 (right) (Right photo: Ezequiel Alfonso).

Fig. 3. Reforestation with *Salix canariensis* before (left) and after (right) the 2010 flash flood event in Verduras de Alfonso gorge (Photos: Ángel Palomares). Take as reference the *Pinus canariensis* in the centre of the valley bottom.

P. canariensis presents frequent irregularities in the functioning of the vascular cambium and the existence of numerous incomplete or missing rings makes dendrochronological analysis difficult, as pointed out in the earliest known trials (Jonsson et al., 2002; Santana, 1999; Santana and Génova, 2003). Furthermore, wound dating was especially complicated because incomplete rings were often formed after injury and sometimes piecewise sequences had to be crossdated as floating series. Aware of these difficulties, we carried out the crossdating processes as accurately and carefully as possible.

Once crossdating had been successfully completed in each tree and in each group of trees, injuries were dated in most cases. Basically, we check the set of tree ring series obtained from each tree, contrasting series from affected and non-affected tissues. Also we check the chronologies of each

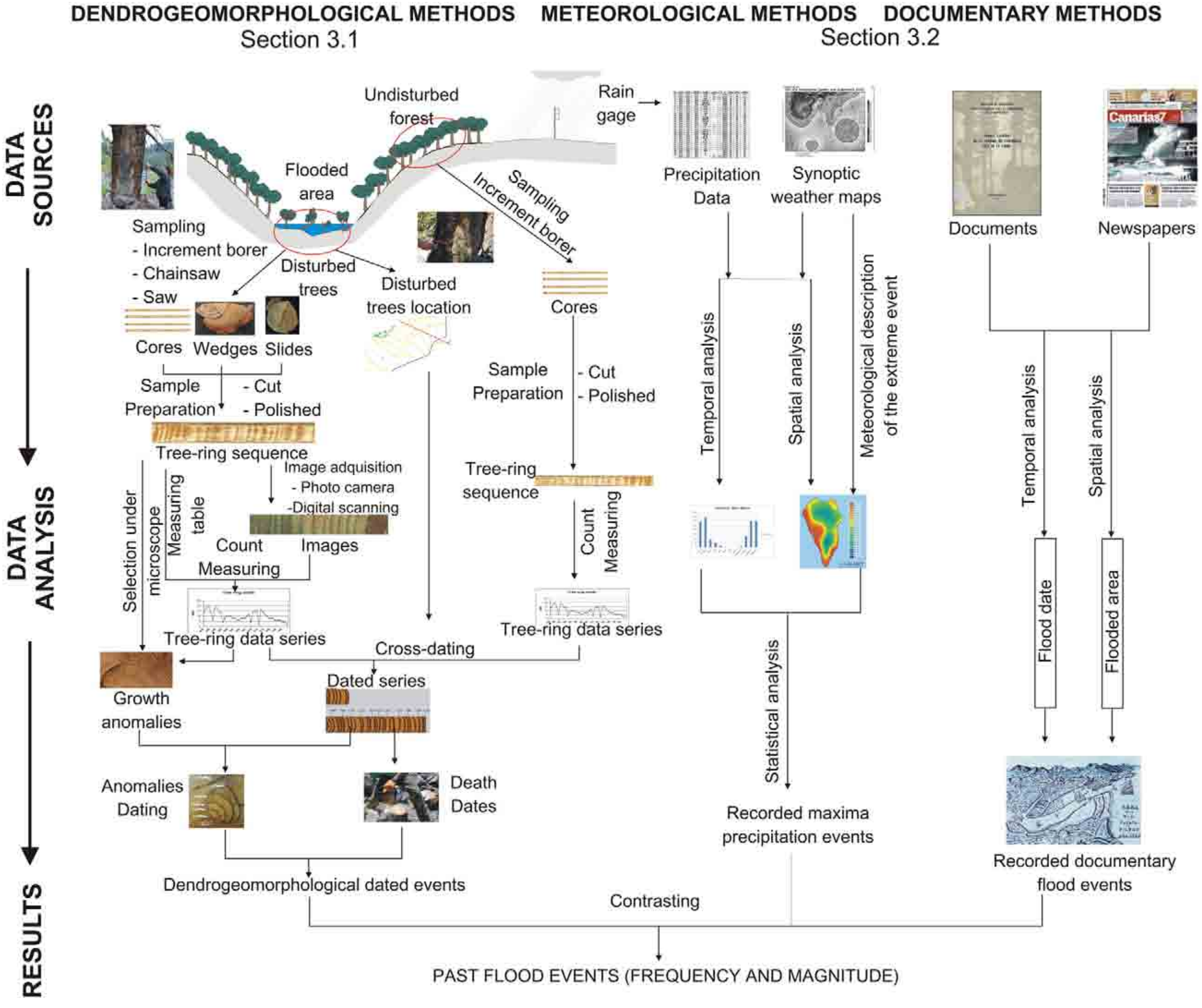


Fig. 4. Methodological synthesis.

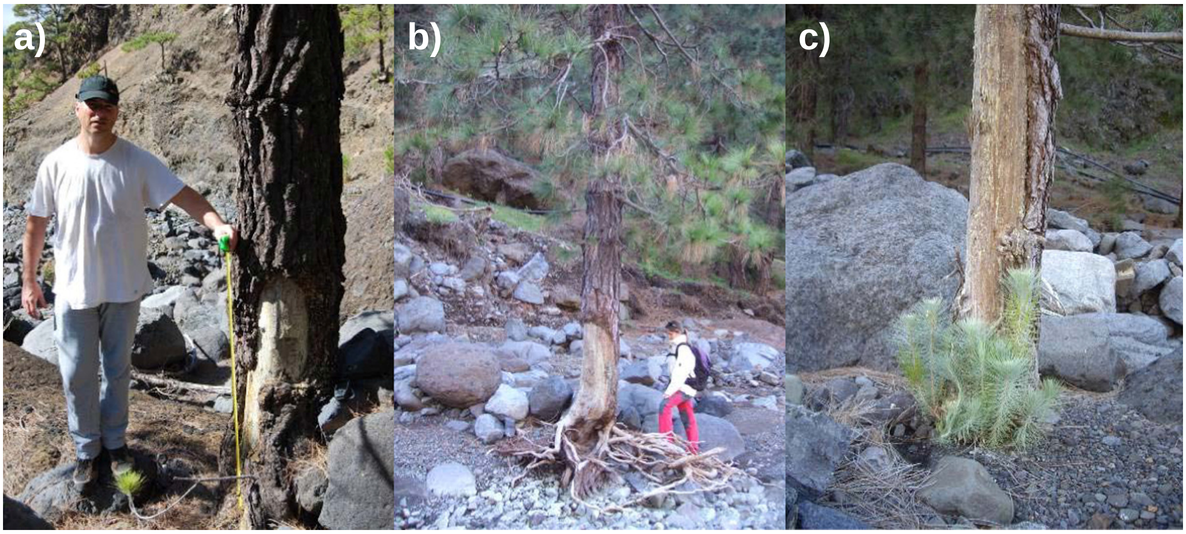
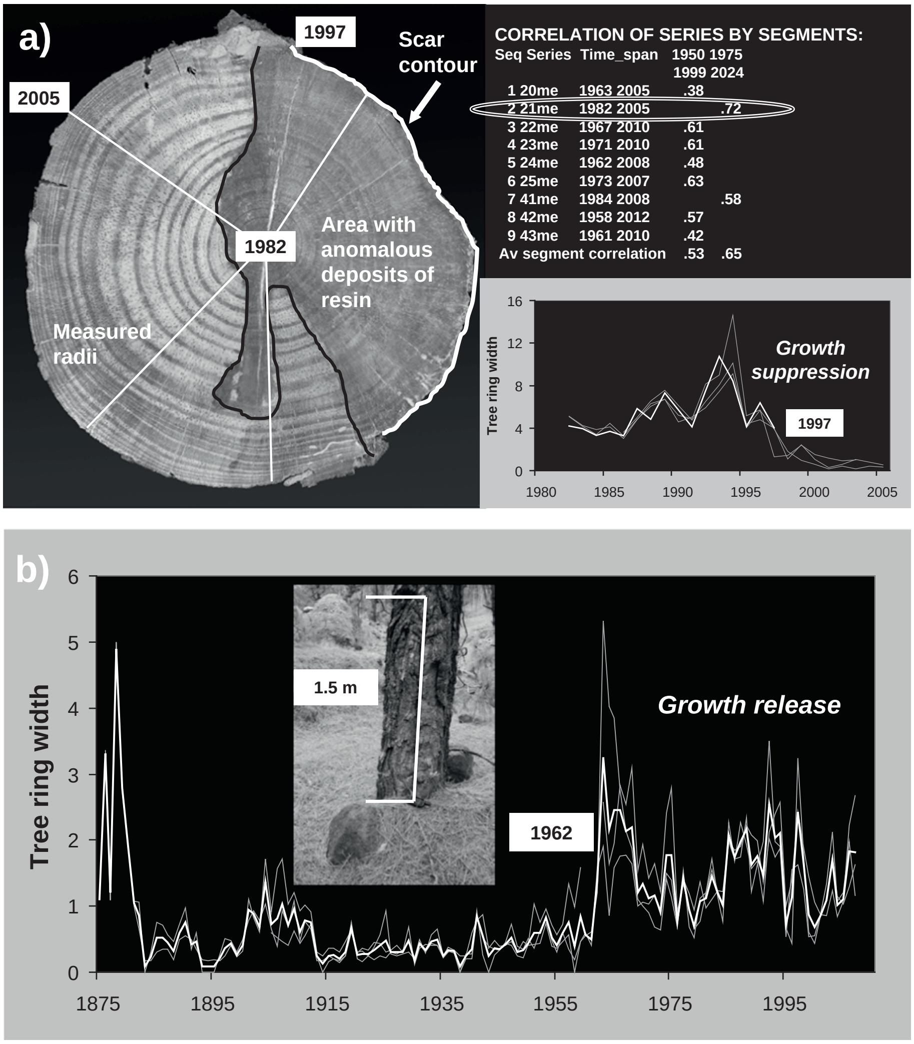


Fig. 5. Examples of injuries on disturbed trees: a) scar; b) large scar and exposed roots; c) large scar and resprouting.

group (i. e. Fig. 6a) and finally a detailed comparison between the disturbed series and the reference chronology have ensured the accuracy/quality of the wound dating.

Growth releases and suppressions appearing synchronously in each group of trees were detected using the Jolts program (Holmes, 1999), in accordance with the suggestions of Rubino and McCarthy



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CORRELATION OF SERIES BY SEGMENTS:
Seq Series  Time_span   1950 1975
                        1999 2024
  1 20me    1963 2005    .38
  2 21me    1982 2005         .72
  3 22me    1967 2010    .61
  4 23me    1971 2010    .61
  5 24me    1962 2008    .48
  6 25me    1973 2007    .63
  7 41me    1984 2008         .58
  8 42me    1958 2012    .57
  9 43me    1961 2010    .42
 Av segment correlation  .53  .65
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Fig. 6. Examples of tree response to damage. a) Growth suppression ending with death of the tree: cross section showing anomalous resin deposits (left), the series correlation with nearby trees (right and above) and graphics of measured radii (right and below). b) Growth release, commonly detected in old trees after 1962 damage, and a picture showing a large scar.

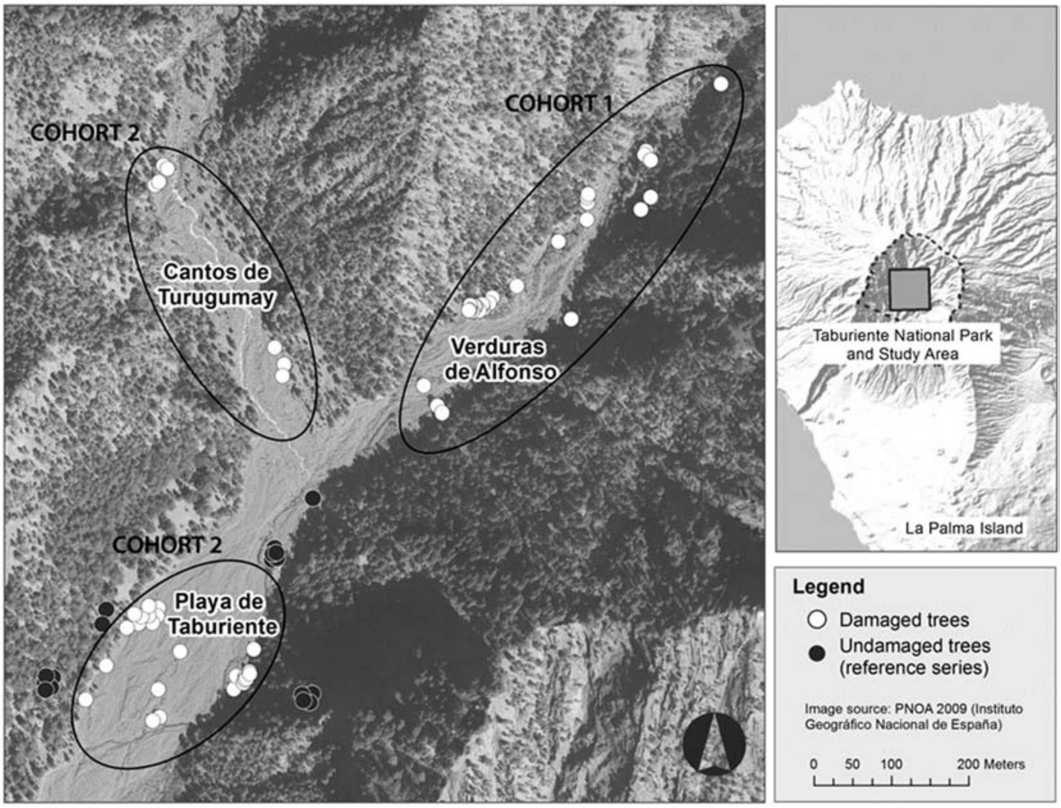

Fig. 7. Detailed study area, with the confluence of the Cantos de Turugumay and Verduras de Alfonso gorges forming the Taburiente River.

(2004) and Copenheaver et al. (2009), as another indicator of the injury dates.

3.2. Meteorological and documentary analysis

The meteorological analysis is focused on identifying the torrential precipitation events capable of generating sudden flash floods. One of the main drawbacks for this research was the lack of meteorological data; only one of the five pluviometers (C106U-Caldera de Taburiente-Taburiente) installed inside La Caldera and in the surroundings of the park and managed by the State Meteorological Agency (AEMET) records daily data (Fig. 1). In addition, its performance has not been optimal: there are only 22 years with a complete record. Alternative rain gauges provide records on a monthly basis; these were installed in the 1980s but the data has not been stored continuously. Since the main aim here is to characterize the rainfall from the point of view of its potential danger, the methodology applied is basically analytical and statistical, and covers the period 1978 to 2012. The work was carried out on different time scales: daily, monthly, seasonal and annual. The variability of inter-annual rainfall is analysed using basic statistics such as mean, standard deviation and coefficient of variation. A second analysis focuses on the monthly scale, to identify the months with the highest concentration of precipitation and characterize its torrential nature. Aspects related to rainfall duration, concentration and intensity during the sampling period of the station are inferred from the daily analysis by using parameters including the Precipitation Concentration Index (Martín-Vide, 2004). Finally, for each of the major rainfall events, a study was carried out of the synoptic meteorological situation generated.

On the other hand, following the methodological guidelines proposed by Barriendos and Coeur (2004) for flood data reconstruction in historical times from non-instrumental documentary sources, preliminary work including data collection, analysis, and storage was undertaken. Several data source types were used for the data collection including, especially, local newspapers, storm chronicles and meteorological ephemerides (Arozarena Villar et al., 1976; Arroyo, 2009) and modern weather news (printed and digital records of national and local daily newspapers). Several interviews were also held with NP rangers and guides, to attempt to define levels and flooded areas in the most recent flood events (1970 to the present) and collect photographs and video recordings.

4. Results

4.1. Tree chronology and tree scar dating

Although synchronizing tree ring growth in *P. canariensis* has been a very complex process due to the presence of numerous anomalies both in the growth rings formed following flood damage and in the undamaged xylem, the number of samples extracted per tree has ensured a robust dating. The main post-damage anomalies detected were indistinct tree-ring marks, discontinuous or absent rings over periods of several years, and anomalous resin deposits (Fig. 6a). For example, a high percentage (average 2.16%) of discontinuous or absent rings was detected (Table 1). Intra-annual wood density fluctuations were also detected in both damaged and undamaged trees.

Six of the sampled trees probably affected by flash floods had no evidence of damage in their tree rings, so finally 242 tree ring growth

Table 1
Characteristics of crossdated growth series. It: mean intercorrelation. MS: mean sensitivity.

	Disturbed trees			Undisturbed trees
	Cohort 1	Cohort 2	Total	
No. trees	25	29	54	10
Diameter (cm)	53 ± 13	37 ± 11	45	55 ± 20
Age (year)	130 ± 13	38 ± 11	84	101 ± 28
Missing rings (%)	3.04	0.87	2.16	1.36
It/MS	0.36/0.45	0.38/0.36	0.34/0.43	0.42/0.40
Chronology	1859–2012	1954–2012	1859–2012	1870–2010

series from 54 trees were selected (17,302 cross-dated rings) for wound dating. Two damaged tree cohorts were differentiated, clearly separated by location (see Table 1, Fig. 7):

- Cohort 1: 25 older trees (estimated mean age 130 years), all located in the Verduras de Alfonso gorge.
- Cohort 2: 29 younger trees (estimated mean age 38 years), mostly located in the Cantos de Turugumay gorge and the Playa de Taburiente.

A reference chronology (undisturbed trees) with 10 trees was also developed (Table 1, Fig. 7), including young and old canary pines, as in the case of the disturbed trees. This chronology (141 years, 1870–2010) was used to test tree growth response after flood events.

63 wounds were dated, in some cases more than one for each tree, with very different percentages in the two cohorts and in total (Table 2). Especially relevant were the injuries occurring in 1962 and in 1997, both presenting a large number of replications (48% and 22%, respectively, of the total number of trees). Wounds dated to 1993 and 2003 are represented in 23% and 20% of the younger trees. Over the last decade injuries have been dated to 2001, 2003, 2007 and 2009, which together account for 18%. Other anomalies in the samples were also found with evidence of injuries but were not reliably dated.

Damage corresponding to the year 1962 was determined in almost all trees more than 100 years old (cohort 1), located in the narrowest gorge in the study area (Verduras de Alfonso, Fig. 7). The scars dated to this year have still not closed 50 years later and are particularly noteworthy, reaching up 3 m length in some cases.

Two types of tree ring growth specific patterns after damage were recognised:

- Growth suppression, in some cases ending with tree death (Fig. 6a).
- Growth release, probably as a result of a large amount of reaction tissue formation, commonly detected in old trees after the 1962 damage (Fig. 6b).

Dendrogeomorphological evidence of flash flood events was compared with growth release and we found that there was a relationship, especially in cohort 1 (the older trees) (Figs. 6b and 8). Thus, other hypothetical dates for flash floods based on releases were searched for and are indicated in Fig. 8. Altogether, this evidence suggests a mean flash flood time interval of 14–15 years. The damage recorded later increased in frequency and the time interval over the last twenty years is 3–4 years, although with much less replication.

4.2. Spatial distribution of flood events as reconstructed from tree rings

Fig. 9 shows the location of the sampled trees with scars dated 1962, 1979, 1993, 1997, 2003, 2007 and 2009. In order to show the areas most affected by the flooding events, sampled trees that already existed in each of the selected years but did not have scars in this year also appear in Fig. 9. All the trees with 1962 scars (the older trees) are located at the Verduras de Alfonso gorge, upstream of the confluence with Cantos de Turugumay. At the Cantos de Turugumay gorge and downstream of the confluence with Verduras de Alfonso no trees with damage were found in this year. The rest of the trees were established after this flood event, forming a second cohort of trees on materials eroded and deposited in 1962.

Table 2
Injuries dated in each year. Undetermined: wounds recognised as growth anomalies but not reliable dated. MH scar: mean scar height.

Year	No. trees damaged	Percentages of injuries dated			MH scar (m)
		Cohort 1	Cohort 2	Total	
1962	26	96%	6%	48%	2,4
1979	5	16%	3%	9%	0,5
1993	7	/	23%	13%	0,5
1997	12	8%	33%	22%	0,8
2001	1	/	3%	2%	0,8
2003	6	/	20%	11%	0,8
2007	2	/	6%	4%	1,5
2009	1	/	3%	2%	1,2
Undetermined	3	12%	/	5%	/

The 1997 event (the second in tree wound replication) was recorded in trees growing throughout the study site established before and after the 1962 event, meaning that the 1997 event was widely distributed. In contrast, the distribution of the other wounds that were dated was more restricted. The 1979 and the more recent events (2007-2009) were detected only on the eastern of the sampling site while the rest were in undifferentiated locations.

4.3. Meteorological rainfall events

The local nature of the precipitation should be noted, since many of the intense rainfall data values are only registered in the immediate area of the Caldera. This is probably due to the orographic effect of the very steep slopes inside the Caldera and to its favourable orientation to winds from the W and SW, characteristic of the main storms affecting the Canary Islands (Máyer, 2011). Thus, the high number of rainfall events registered is not surprising and even more episodes may have occurred, since there are some gaps in the data series.

December and January are the wettest months with most rainfall, which is clearly seasonal with 56% of the precipitation occurring in winter. The torrential nature of this rainfall is one of its most significant features: Table 3 shows that in some months the rainfall is more than 7 times the mean value (January 1979), or more than 6 times the mean (February 2010). A total of 200 mm in a single day was recorded on 11 days in only 22 years; this amount is a very significant percentage of the total monthly and annual precipitation (average of 40% and 25% respectively). Analysis of the daily rainfall intensity inside the Caldera shows that the intensity of just over a third of the precipitation tends to be weak or very weak (less than 5.0 mm); however, on a relatively high percentage of days (5%) the precipitation exceeds 100 mm in 24 h.

The Precipitation Concentration Index (Martín-Vide, 2004) enables a further assessment of the hazardousness of the rainfall, obtaining the value 0.7 for the Taburiente series. This means that 80% of the rain occurs on 25% of the days with heaviest rainfall. This value is similar to those found elsewhere in La Palma and also in the rest of the Canary Archipelago (Máyer and Marzol, 2012), and is also very close to values obtained by Cortesi et al. (2012) in various regions in southern Europe. With regard to the duration of the extreme rain, the probability of it falling in a single day is higher than 50%. The accumulated precipitation in these sequences ranges from 14% to 9% of the annual rainfall (Fig. 10). The longest period of consecutive rain days occurred between 12 and 27 January 1979, with 1108.9 mm collected over those 16 days.

The probability for December to be the wettest month of the year is 32%. This probability decreases to 23% for January, 14% for February and 9% for April, October and November. The intensity of the amount of water falling on the wettest day of the year is usually higher than 100.0 mm in 24 h. However, the high number of days where rainfall exceeds 200 mm/24 h should be noted (Table 4), because these represent 45% of the rainiest days.

4.4. Multidisciplinary flash flood record

Fig. 12 compiles the information available for the past 50 years, including the flash floods recorded from damaged trees and in other flash flood proxies, such as meteorological data and documental sources. Among the flash floods dated by dendrogeomorphological techniques, those in 1962, 1979, 2001, 2007 and 2009 match other data sources.

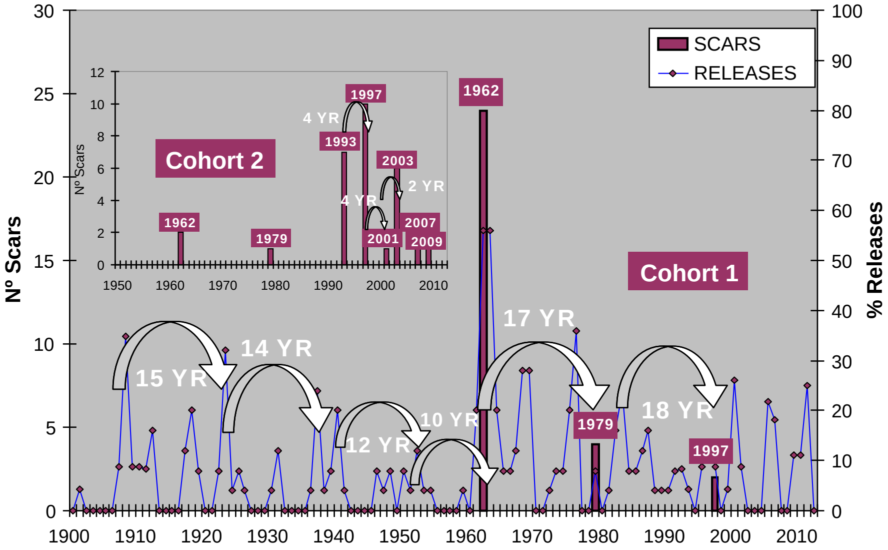

Fig. 8. Evidence of injury and time interval.

All the dendrogeomorphological evidence analysed (i.e., wound number and size of affected trees, growth anomalies, tree age and location) indicates that the 1962 event is the largest to occur over the past 50 years at the head of the Las Angustias river. This was a very powerful event; the affected trees are currently located away from the riverbed indicating high erosion rates and changes in the course of the riverbed. We have not found other old damaged trees elsewhere, so presumably they were uprooted during this flash flood. Although there is no local meteorological data available in this year, the event is supported by documental references (Arozarena Villar et al., 1976, local newspaper) and

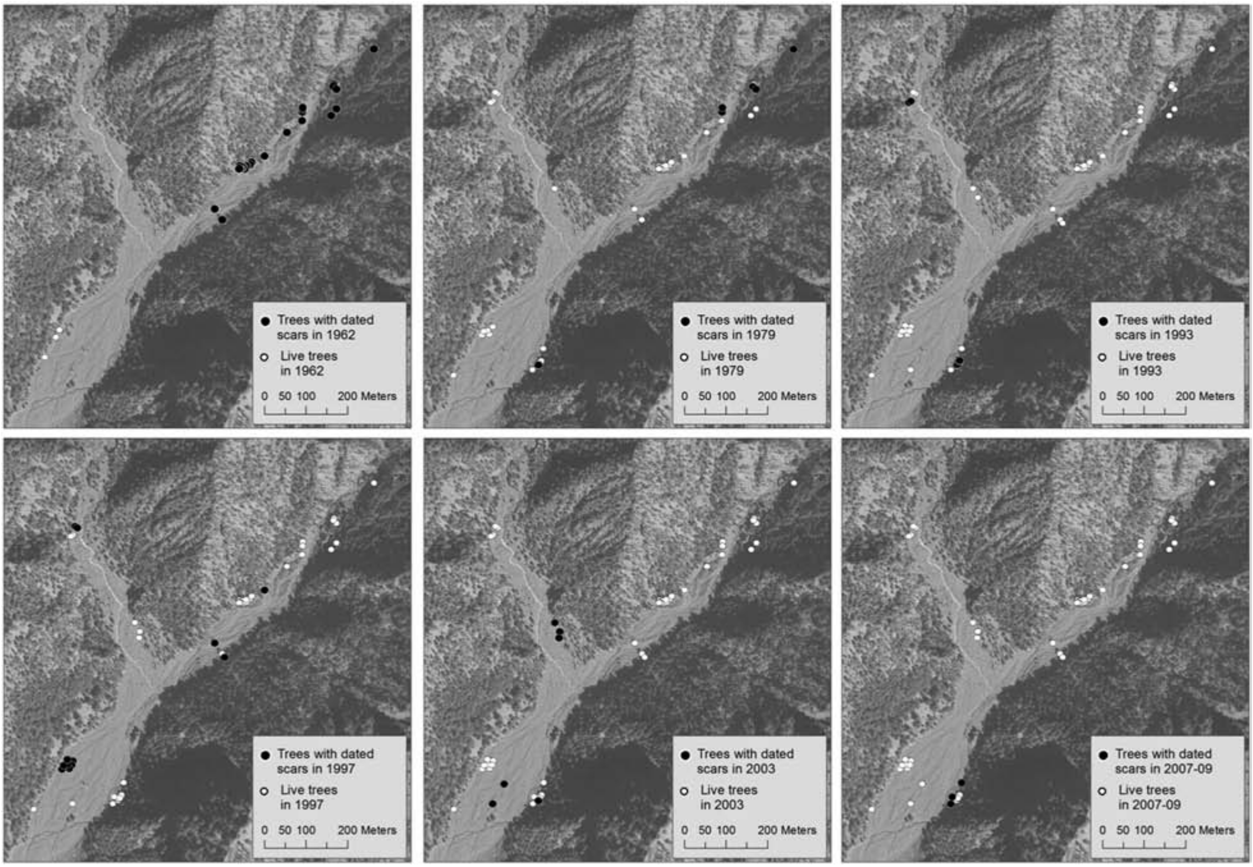

Fig. 9. Location of trees damaged by the different flood events dated dendrogeomorphologically on a 2009 satellite image. Each map indicates the damaged trees in that year and all existing trees.

Table 3
Main characteristics of maximum monthly precipitation at the Taburiente rain record (1978–2012). No.: Number of days per year with heavy rainfall. Source: AEMET.

Month	J	F	M	A	M	J	JL	A	S	O	N	D
Mean (mm)	213.3	125.9	126.3	54.3	15.0	1.4	2.5	1.5	13.8	99.6	138.1	227.1
Max. (mm)	1626.1	808.1	499.0	214.2	67.7	15.0	54.2	13.6	70.6	328.1	517.3	703.2
Year	1979	2010	2007	1980	1996	2009	1979	1989	1990	1993	1988	2009
Daily max. (mm)	243.9	399.3	279.0	93.0	39.0	15.0	54.2	9.0	57.0	180.0	162.0	226.0
No.	3	4	1	1	0	0	0	0	0	5	2	6
Year	1980	1978	2007	2002	2011	2009	1979	1989	2010	1979	1987	2009

we searched for data from other meteorological stations on La Palma island to corroborate the existence of this heavy rainfall event (Fig. 11a).

Other evidence-based information events between the different sources occurred in 1979, 2001, 2007 and 2009, although the dendrogeomorphological record is sparse. Other years with damaged trees (1993, 1997 and 2003) have no events recorded in either meteorological or documental data sources.

As seen in the weather maps (Fig. 11), heavy rainfall in this area is a response to the expansion of polar air masses in the middle and upper layers of the atmosphere. Surface frontal storms cross the island from west to east, producing abundant rainfall, as happened during the month of January 1979. In that month various low-pressure systems approached the islands and lead to rainfall of over 200 mm/24 h on 5 different days (05, 07, 17, 23 and 26 January).

5. Discussion

5.1. New contribution issues

This study develops dendrogeomorphological analysis applied to flash floods in lower latitudes; it is unique for subtropical, tropical or equatorial areas (Benito and Díez-Herrero, 2015), although there are numerous precedents in the centre of the Iberian peninsula (Díez-Herrero et al., 2013a) and in other areas in temperate mid-latitudes (Stoffel et al., 2010). The dendrogeomorphological data is also compared with available meteorological and documental information to obtain a multidisciplinary flash flood record.

This research is focused on three issues. First, to determine how flash floods affect *P. canariensis* and if this species is potentially useful for the reconstruction of flash flood events. Second, to obtain a record from dendrogeomorphological evidence to estimate the damage time interval and area affected; these data have then been contrasted with meteorological records and documental sources to establish the most complete possible flash flood record. At this point it should be noted that there are uncertainties in the different data sources used in this multidisciplinary study. Finally, within the fields of applied ecology and dendrogeomorphology, the results of this case study can be used to develop a Flood Risk Plan for the Caldera de Taburiente NP; this plan is essential due to the frequent historic flash flooding events that have caused casualties and financial damage.

5.2. How flash floods affect P. canariensis

The effects of fire damage in tree rings of *P. canariensis* have already been analysed (Rozas et al., 2011); the present dendrogeomorphological study extends the dendroecological applications of this species. However, there are difficulties to be taken into account in synchronizing growth

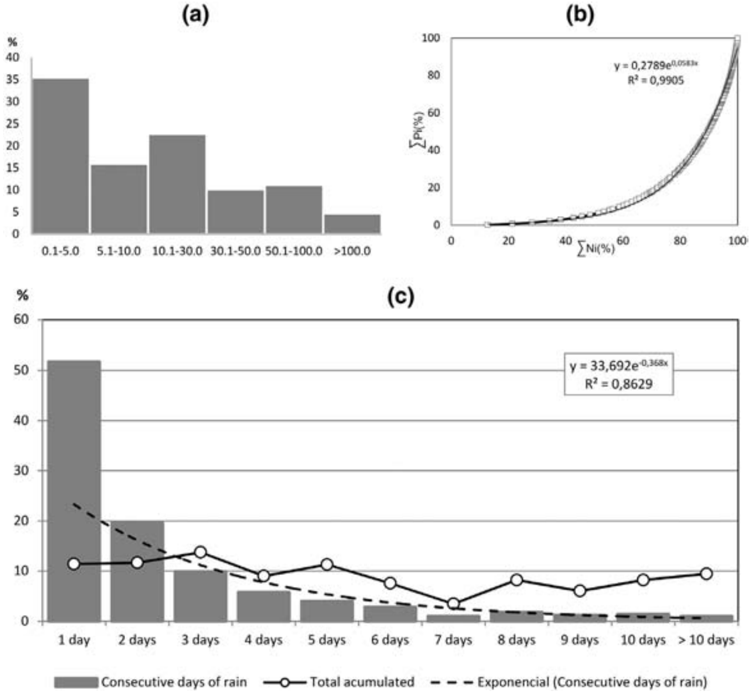

Fig. 10. Taburiente rain gauge (1978–2012): (A) Frequency of maximum rainfall in 24 h, (B) Daily Precipitation Concentration Index, (C) ratio of rainfall event duration to amount of rainwater collected.

Table 4
Rainfall ≥ 200 mm/24 h at Taburiente weather station. Source: AEMET.

Date	10/02 1978	23/01 1979	25/01 1980	27/02 1986	23/01 1987	04/12 1991	22/12 2000	13/03 2001	19/03 2007	23/12 2009	15/02 2010
Precipitation (mm)	399.3	210.0	243.9	217.0	240.0	208.0	209.5	200.0	279.0	226.0	241.1

series as previous dendrochronological studies have already indicated. In our case study a high percentage of discontinuous or absent rings, higher than those in undamaged trees, was also detected after damage. Moreover, several of the old Canary pines that were sampled had large wounds with great calluses with abnormally wide and sometimes indistinct tree-ring marks. To overcome these difficulties, we often extracted more than two cores per tree to ensure reliable dating, which we recommend in future work with this taxon.

We found that the most specific tree responses after flood damage in *P. canariensis* are (i) growth suppression, when the damage has been so great that growth has decreased for several years and tree death sometimes occurs; and (ii) growth release, commonly detected in old trees. It

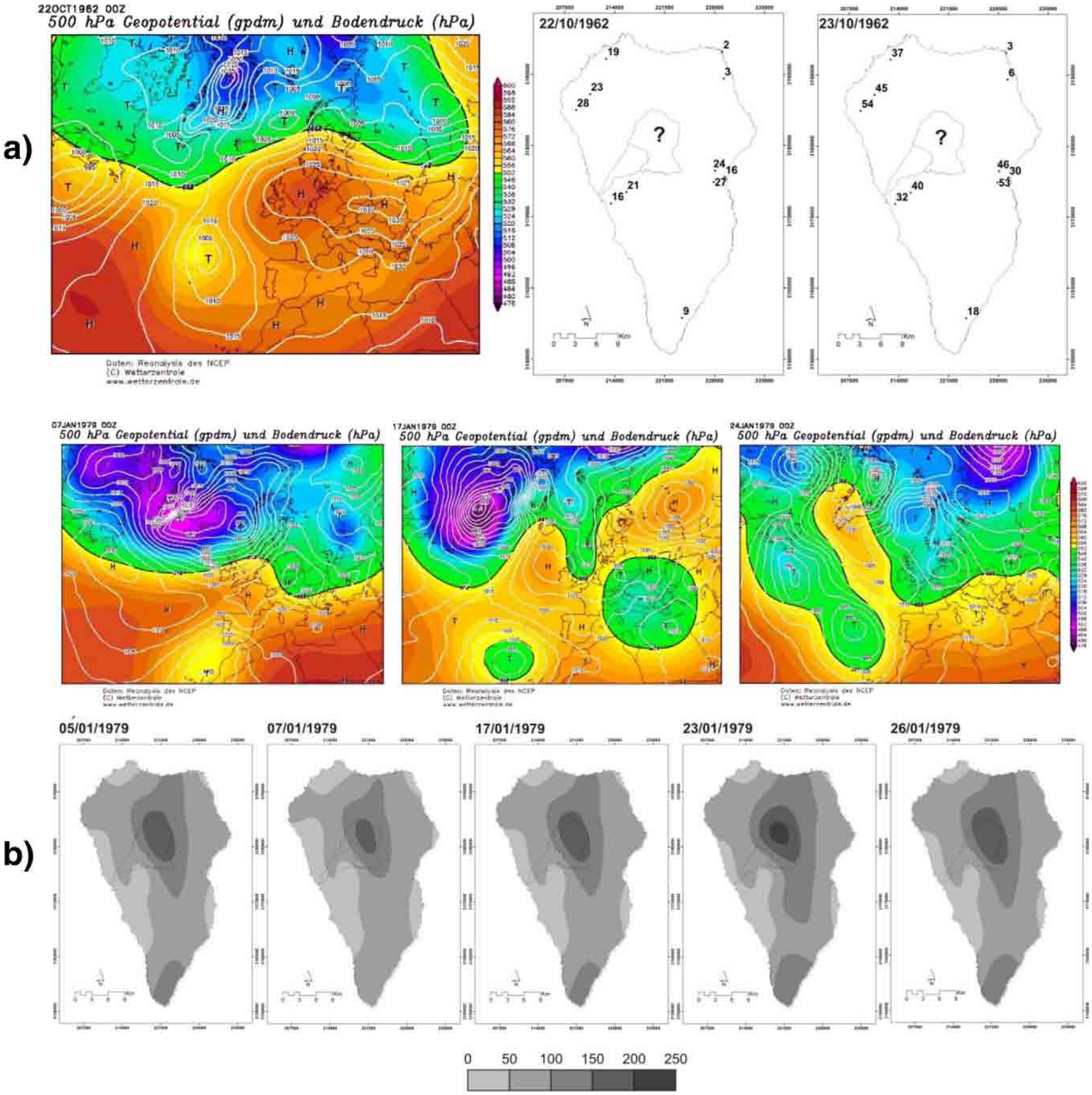

Fig. 11. a) 1962 event: 500 hPa weather map, surface isobars and precipitation records on the La Palma island. b) 1979 event: 500 hPa weather map, surface isobars and rainfall distribution on the La Palma island.

was also found that if the wounds are large and the trees are young then resprouting occurs, in the same way that Canary pine usually responds to other types of damage (Climent et al., 2004).

5.3. The multidisciplinary record

We have obtained a multidisciplinary flash flood record that is as complete as possible by using available dendrogeomorphological, meteorological and documental evidence (Fig. 12).

Sixty-three wounds from 54 trees with very different evidence percentages were dated, covering the past 50 years. Moreover, the relationship between dated scars (1962, 1979 and 1997) and growth release in older trees, not present in reference trees, enable us to put forward a hypothesis for flood recurrence. Given these dated events and those that are indirectly dated, the average time interval for flash floods is established to be 14–15 years; this would be reduced to 3–4 years for the latest low replication injuries dated in younger trees. However this average time interval contains considerable uncertainty as there is no certainty that all the events occurring at a particular site have been dendrogeomorphologically dated (Ruiz-Villanueva et al., 2010; Zielonka et al., 2008). Among the flash floods dated by dendrogeomorphological techniques, those in 1962, 1979, 2001, 2007 and 2009 match other data sources, although there is no local meteorological data available for 1962 (Fig. 12). The reasons for the mismatch between the three data sources studied and, therefore, the interest to develop a record with all of them, are discussed in the next section.

5.4. Uncertainties in a multidisciplinary flash flood record

5.4.1. The dendrogeomorphological record

In the Caldera de Taburiente, the dated flash flood impact on trees was confirmed to be related to their geographical situation and age. However, at each point in the history of a flash flood, the effect on vegetation varies depending on the trees' position; however this is dependent on the torrent system dynamics (Ruiz-Villanueva et al., 2010). For example, there is not necessarily any direct general correlation between the dates of the greatest flow events and the quantity and intensity of the dendrogeomorphological evidence. In fact, the hydrological flash flood events which are best recorded in the form of dendrochronological evidence are, a priori, the extraordinary events of intermediate magnitude. The catastrophic events of greater magnitude uproot and destroy all the trees on the valley floor, leaving hardly any evidence; and the ordinary events of lower magnitude leave little evidence in terms of number and replication which would allow them to be easily detected (Ruiz-Villanueva et al., 2010). In this respect, we noted during the specific case study presented here that numerous trees were uprooted and swept away by flooding (Fig. 3), and two of the sampled trees disappeared in the latest floods in 2013. Added to all this is the close proximity in time of successive events which may mask or screen other earlier or later events of different magnitudes since e.g., a later event of greater magnitude would destroy all the dendrogeomorphological evidence of a previous, less intense event (Ballesteros et al., 2013). This implies such great skew that it would require event by event interpretation of the different data records, taking into consideration the time lapse between them.

5.4.2. The meteorological and documentary record

An important source of mismatch in the comparative analysis of the dendrochronological, documental and meteorological sources is that the meteorological series are short and barely representative. On an island and in a basin with such extraordinary orographic contrasts and a clear directionality in the provenance and evolution of the meteorological systems which produce the precipitation, only one rain record is available in the study area, and it has only been in place since 1978. These data are not spatially representative either, as the local nature of some precipitation events (convective and frontal phenomena with important orographic components), means that they cannot be recorded in this single rain record, or even in the pluviometers located in the surrounding areas, nearly always at low altitudes near the most important inhabited areas.

In addition to the usual difficulty that stems from the inclusion of historical data in statistical analyses (Francés, 2004), the spatial skew comes together in the case of the events documented in this sector of the island of La Palma, as it is at a considerable distance from documentation centers which produce reports and information, and only the events of greatest magnitude were recorded. Moreover, people's different historical perceptions of the damage may also arise, resulting in mismatching in the calibration of each event. Finally, even if all the uncertainties can be resolved, and each past event can be successfully linked to a date of occurrence and magnitude (normally flow rate), including it as non-systematic data in a statistical flow rate analysis is complicated.

5.4.3. The non-linear nature of the rainfall-runoff process and its effects

Explanations about the mismatching between events recorded in documents or in the systematic record of intense precipitation and those deduced from the dendrochronological analysis must include the non-linear nature of the rainfall-runoff process and its impact on riparian vegetation. One of the main sources of uncertainty in our dendrogeomorphological results is the existence of a hydraulically movable alluvial bed. This implies that the riverbed configuration may change significantly from one event to the next, as we have confirmed by comparing historical series of aerial photos, or multi-temporal field photos. This may explain why no recent damage was identified in most of the older trees: it was found that they were located at some distance from the active riverbed for many years. In contrast, in younger trees, damage occurred every 3–4 years over recent decades, affecting different groups of trees depending on the specific course of the riverbed during the event.

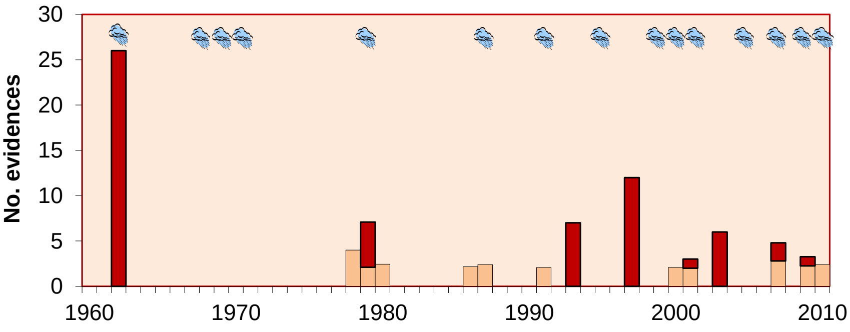

Fig. 12. Compilation of multidisciplinary proxies of flash flood events available for the past 50 years. Red column: number of damaged trees; orange column: rainfall ≥ 200 mm/24 h/ 100. 🌧: hemerographic recorded event. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.4.4. The solid load transport

Another feature which complicates or even prevents flow estimates from palaeostage indicators, is the solid load transport during flash floods. In fact, as can be seen from field-based evidence (washout deposits, erosive capacity, excessively high palaeostage indicators, …), the solid load plays a crucial role in the torrential phenomena in the Caldera de Taburiente gorges. This solid load is in both the debris bedload (sand, gravel, pebbles, boulders and large boulders) and in the floating load (tree logs, branches, root systems, etc.) and significantly modifies the flow hydrodynamics. This solid load raises the height of the water sheet and increases the fluid density and viscosity and, therefore, its transport capacity with a feedback effect (Castillo, 2004). The role of the debris bed load is somewhat similar to that of the floating woody load, leading to important hydrodynamic and turbulent changes and to effects derived from the generation and position of the dendrogeomorphological evidence itself (Ruiz-Villanueva et al., 2014a, 2014b). Therefore, it becomes necessary to determine, firstly, the type of phenomenon, which may range from a rock avalanche to a clear water flood, including debris flow, hyperconcentrated flow or debris flood. Furthermore, the same event may evolve in space and time through various of these phenomena, which makes interpreting past events from the available evidence extremely complicated.

All these uncertainties and more, which restrict the application of the obtained results, are not exclusive to this case study. Instead, they are common to all the gorges and ravines in the Canary Islands, to most of the Macaronesian archipelagos, and to many mountains in the Mediterranean basin, especially in ungauged reaches. However, confronted with the lack of gauge data, multidisciplinary information on flood flow frequency derived from dendrogeomorphological, meteorological and documentary evidence is shown as an interesting approximation. And even though this multidisciplinary data is not statistically reliable, it is justified as the only evidence objectively available and therefore useful in flood risk and hazard assessment.

6. Conclusion

Dendrogeomorphological studies of *P. canariensis*, combined with meteorological analyses and documental sources provide the best possible record of flood events in the Caldera de Taburiente NP. The data are, however, subject to some uncertainties and mismatching, due to missing events as a consequence of the limitations of each method. The multidisciplinary record presented here is a highly valuable input in ongoing developments of hazard analysis and are definitely needed to improve the management of one of the most complex and dynamic Spanish national parks from a dendrogeomorphological point of view.

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