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

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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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.