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Unravelling past flash flood activity in a forested mountain catchment of the Spanish Central System

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SUMMARY

Flash floods represent one of the most common natural hazards in mountain catchments, and are frequent in Mediterranean environments. As a result of the widespread lack of reliable data on past events, the understanding of their spatio-temporal occurrence and their climatic triggers remains rather limited. Here, we present a dendrogeomorphic reconstruction of past flash flood activity in the Arroyo de los Puentes stream (Sierra de Guadarrama, Spanish Central System). We analyze a total of 287 increment cores from 178 disturbed Scots pine trees (*Pinus sylvestris* L.) which yielded indications on 212 growth disturbances related to past flash flood impact. In combination with local archives, meteorological data, annual forest management records and highly-resolved terrestrial data (i.e., LiDAR data and aerial imagery), the dendrogeomorphic time series allowed dating 25 flash floods over the last three centuries, with a major event leaving an intense geomorphic footprint throughout the catchment in 1936. The analysis of meteorological records suggests that the rainfall thresholds of flash floods vary with the seasonality of events. Dated flash floods in the 20th century were primarily related with synoptic troughs owing to the arrival of air masses from north and west on the Iberian Peninsula during negative indices of the North Atlantic Oscillation. The results of this study contribute considerably to a better understanding of hazards related with hydrogeomorphic processes in central Spain in general and in the Sierra de Guadarrama National Park in particular.

1. Introduction

Flash floods represent one of the most common natural hazards in mountain environments (Borga et al., 2008, 2014). The process is characterized by high flow velocities and important sediment charge causing severe damage and socio-economic losses, especially along the channels and on alluvial fans. In headwater catchments, torrential processes are moreover the main geomorphic agent responsible for landscape evolution (Carling, 1986; Foulds et al., 2014). From a scientific perspective, the understanding of the temporal dimension of these processes as well as their climatic triggers and subsequent effects on the environment are still a challenge worldwide, probably owing to the frequent occurrence of these processes in sparsely populated areas where archival data and systematic records are usually scarce (Mayer et al., 2010) or unrepresentative (Ayala-Carcedo, 2002). The lack of data on past activity therefore hampers the analysis of flash flood processes and calls for the use of alternative geomorphic approaches (Ibsen and Brunsden, 1996; Jakob, 2005). In this regard, paleohydrologic techniques allow to track the history of past (flash) flood events in ungauged catchments (Baker et al., 2002; Benito et al., 2003; Baker, 2008), and consequently, to improve links between process dynamics, climatic conditions and related hazards (Kingston et al., 2007; De Jong et al., 2009; Merz et al., 2014).

In mountain catchments, trees are frequently present next to torrential channels and on their banks, and can thus be used to

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reconstruct past flood activity with dendrogeomorphic methods (Stoffel et al., 2010). The systematic analysis of growth-ring series from trees disturbed by hydrogeomorphic processes (Stoffel and Wilford, 2012) typically yields valuable records of past events in ungauged mountain catchments with very high spatial and temporal accuracy (Shroder, 1980; Stoffel et al., 2010; Stoffel and Corona, 2014).

Dendrogeomorphical techniques have first been applied in fluvial geomorphology (Sigafoos, 1964; Sigafoos and Hendricks, 1961). However, despite that the utility of botanical evidence in paleohydrology has been recognized by many researchers (i.e. Baker, 1987; Hupp, 1988), tree rings have been used much less frequently as compared to other lines of evidence of paleofloods (e.g., slackwater deposits; Benito and Thorndycraft, 2004). The large potential of dendrogeomorphic tools for the assessment of frequency and magnitude of past events has been demonstrated in recent works (e.g., Ballesteros et al., 2011; Gottesfeld and Gottesfeld, 1990; Gottesfeld, 1996; Ruiz-Villanueva et al., 2010; Schraml et al., 2013; St. George and Nielsen, 2003). Further research has focused on changes in the spatial geomorphic patterns of processes (Arbellay et al., 2010; Bollschweiler et al., 2008; Stoffel et al., 2008) and on the seasonality and related climatic drivers of hydrogeomorphic processes (Schneuwly-Bollschweiler and Stoffel, 2012; Stoffel et al., 2011).

Here, we present a case study focusing on the spatio-temporal reconstruction of past flash flood activity in the Arroyo de los Puentes stream (Sierra de Guadarrama National Park, Spanish Central System). We analyze 178 Scots pine trees (*Pinus sylvestris* L.) disturbed by past flash flood events and couple this data with a large local historical forest management and climatic dataset of the study site to (i) report on the flash flood history of the stream during the last 212 years, and to (ii) identify local meteorological conditions which most likely acted as triggers of flash flood events during the past 83 years for which meteorological records exist locally.

2. Study site

The study site is located in the catchment known as *Arroyo de los Puentes* and its tributaries, located on the northern slope of the Guadarrama Mountains (Sierra de Guadarrama National Park, Spanish Central System, 40°47′37″N, 3°55′14″O; Fig. 1). The catchment covers approximately 2.5 km^2 and extends from the Bola del Mundo at 2258 masl to the alluvial fan area at 1500 masl. The average slope in the main channel is 9° (range: 7–18°).

The upper part of the catchment is occupied by extensive accumulations of unconsolidated gneissic materials prone to gelifraction. Water circulation in the source area is mostly subsuperficial, although several well-defined channels exist. The most characteristic geomorphic features in the central part of the catchment (between 1800 and 1600 masl) are linked with torrential activity, such as levees, lobes and well-defined avulsion channels. In this channel segment (at 1660 masl), Majabarca stream joins the main channel and exhibits several trees affected by floods. In the lower part of the catchment (from 1550 to 1480 masl) the valley opens and the gradient decreases, creating an alluvial fan at the confluence of Arroyo de los Puentes with Arroyo de las Pintadas stream. The fan covers an area of approximately 0.03 km^2 ha and its surface is crossed by several channels.

The region is dominated by a Mediterranean climate with continental influence that could be considered as 'humid continental with warm summers' (type 'Dsb': Köppen-Geiger classification, Peel et al., 2007). The study zone also has some Atlantic influence in the regime of rainstorms and is characterized by mild summers and long, cold winters. Average annual precipitation is 1326 mm with maximum rainfall in April, May, October, November and December (AEMET, 2011). Mean annual temperature is 6.5 °C at 1890 masl with mean monthly temperatures ranging from 2.9 °C in winter to 9.9 °C in summer, reaching up to 31.8 °C in August and −20.3 °C in December, as extreme values.

The study area is located in Montes de Valsaín (hereafter, Valsaín Forest), an extensive, managed *P. sylvestris* L. forest (10,700 ha). The forest is unique in the Mediterranean context owing to the extremely detailed record of forest management interventions started at the end of the 18th century and its management in general over more than eight centuries (Dones and Garrido, 2001).

3. Materials and methods

3.1. Geomorphic mapping and sampling strategy

A geomorphic characterization of all of the features related to hydrogeomorphic processes in the studied catchment was carried out by combining aerial imagery (cell size: 0.25 m), LiDAR data (cell size: 1 m) and field surveys. All geomorphic features were digitized using ArcGIS™ version 9.3 (ESRI, Redlands, CA, USA, 2009). Disturbed trees – namely wounded, tilted, decapitated or buried trees – located along the channel banks and/or on the fan were sampled following standard procedures in dendrogeomorphic studies as described in Stoffel and Corona (2014). Trees with possible disturbances by any process other than hydrogeomorphic (such as rockfall or human activities) were not been included in analysis. Trees were sampled with increment borers and two increment cores per tree were extracted with sampling positions being chosen according to the nature of the disturbance (Stoffel et al., 2005a). Samples were taken at the contact between the scar edge and the intact wood tissue to make sure that the entire tree-ring record was obtained (Schneuwly et al., 2009a,b). In parallel, undisturbed trees were also sampled in the upper and lower parts of the catchment to build a reference chronology and to identify pointer years for a reliable and precise cross-dating with disturbed trees (Touchan et al., 2013). Tree-ring widths were converted into width indices by standardizing raw data using ARSTAN software (Cook, 1985).

3.2. Tree-ring analysis and flash flood chronology reconstruction

Samples were prepared and measured following standard dendrochronological procedures (Stoffel and Corona, 2014). Individual growth series were obtained for each tree and cross-dated with the reference chronology, both visually and through statistical procedures (Stoffel et al., 2005a,b). Signatures of past flash flood activity were then identified on the increment cores and included injuries, callus tissues, compression wood, abrupt growth increase and/or growth suppression. Because *Pinus* spp. do not form tangential rows of traumatic resin ducts (or TRD, Stoffel, 2008), the seasonality of flash flood events had to be based on the position of wound borders within the increment rings.

For the separation of flood signals from noise related with other external processes affecting trees, we applied the weighted index value (W_{it}) as defined by Kogelnig-Mayer et al. (2011). This index considers the number and the intensity of growth disturbances (GDs) within each tree-ring series and the total number of trees available for the flash flood reconstruction. The W_{it} is calculated for each year of the reconstruction and considers differences in the intensity of tree reactions to mechanic disturbance related with past events. We screened recent publications to define appropriate thresholds for the identification of past hydrogeomorphic events (Corona et al., 2014; Schneuwly-Bollschweiler et al., 2013; Stoffel et al., 2011). In addition to the thresholds, we also visually analyzed the spatial distribution of the affected trees along the