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Hydrogeomorphic activity in ungauged Mediterranean gorges: Specifics of tree ring data-based study

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ABSTRACT

Hydrogeomorphic processes (HP) are dangerous natural hazards, particularly in areas with increasing settlement. The Mediterranean region is a highly endangered area, particularly due to its high sensitivity to environmental changes. Chronological information about past events occurrence is crucial for modelling its development in the future. This study aims at building the chronology of past HP in two ungauged gorges along the southern coast of Crete using dendrogeomorphic methods. In total, 188 wounded trees revealed information about 13 events in nine various years over the past 80 years. Dendrogeomorphic records were obtained from Italian cypress (*Cupressus sempervirens* L.) – a tree species that has never before been used for palaeoflood analysis. Limitations of this species are presented and discussed. Moreover, the analysis of the growth responses of Italian cypress to HP events at the anatomical level resulted in important findings regarding its possible use for dating in the future. The reconstructed chronology of events expresses the number of HP events over past decades. The spatiotemporal patterns of affected trees suggest various characters of the process during individual events. Moreover, the type/character of the process is most likely changed even in the longitudinal profile of the gorges during the same event.

1. Introduction

Hydrogeomorphic processes (HP) are considered one of the most dangerous natural hazards (Stoffel and Wilford, 2012; Benito et al., 2015; Hooke, 2015; Ristić et al., 2012). Annually, they cause serious damage to human infrastructure and thousands of fatalities (Pereira et al., 2017) resulting in huge financial expenses for damage remedy. Moreover, the frequency and magnitude of HP are changing, particularly with the present conditions of climate and environmental changes. The Mediterranean region is one of the most sensitive and vulnerable areas of flooding, with frequent occurrence of flash floods and another types of HP (Tsanis et al., 2011; Benito et al., 2015). This flashy nature is even more dramatic in the mountainous and coastal areas where the valleys have deep and narrow gorges. In such conditions, the HP wave may consequently endanger transport infrastructure and the tourism industry (Hooke, 2016, 2015). Generally, systematic information about the occurrence of HP and their frequency and magnitude is mostly lacking in the Mediterranean due to the sparse network of gauging stations. HP records from gauge stations in very narrow gorges are particularly difficult to obtain due to the too-high magnitude or too-destructive character of individual events in these features (Ruiz-Villanueva et al., 2010). High-magnitude events can damage or even destroy the gauge by transporting sediments or stems and branches. Documentary proxies of past HP occurrence such as records from chronicles, cadastral inventories, local newspapers, and reports on water/forest management are scarce; human memory is selective (Mayer et al., 2010), and HP events in uninhabited areas are often not recorded. Thus, the HP chronologies are often very short, incomplete, or even missing. Chronological reconstruction usually simplifies the HP as a "flash flood" (Ballesteros et al., 2015a, 2015b, 2015c). However, different types of torrential processes (e.g., debris flows, debris floods, or hyperconcentrated flows) may occur at or alter even one longitudinal profile due to the decreasing channel gradient and changing conditions of sedimentary supply (Bodoque et al., 2015; Tichavský et al., 2017).

Chronological data about past HP occurrence are crucial for hazard analysis (Ballesteros et al., 2012). Dendrogeomorphic dating (Alestalo, 1971) is an alternative method for obtaining the chronology of past HP events in forested catchments. In certain environments, riparian vegetation is a sensitive recorder of high water levels in channels and floodplains. Sediments, tree stems, and branches entrained in floodwaters can encounter living trees and affect their growth due to wounding, stem tilting or root exposure (Stoffel and Wilford, 2012; Osterkamp et al., 2012). Trees react to such events in the form of (i) scars and callus tissue, (ii) tangential rows of resin ducts (only selected

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coniferous species), (iii) abrupt growth changes (release or suppression), or (iv) reaction wood formation (Sigafoos, 1964). Moreover, the height of scars on tree stems can be used as a palaeostage indicator of past HP activity (Ballesteros et al., 2011a, 2011b; Bodoque et al., 2015). Tree ring-based methods in palaeoflood reconstruction can supply information about both the frequency and approximate magnitude of events. This approach was successfully applied in North America (Sigafoos, 1964; Harrison and Reid, 1967; Phipps, 1970; Helley and LaMarche, 1973), the Carpathian Mountains (Ballesteros et al., 2015a, 2015b, 2015c; Šilhán, 2015), Central Spain (Ruiz-Villanueva et al., 2013; Rodriguez-Morata et al., 2016) or Austrian Alps (Mayer et al., 2010). Except for one study/paper (Diakakis, 2013), dendrogeomorphic reconstructions from the eastern Mediterranean are still lacking. Past HP reconstruction is particularly important for this region because of the expected increase in high-magnitude HP occurrence in the future (Tsanis et al., 2011).

One of the possible causes of the lack of studies is the specific vegetation cover in the narrow valleys of the Mediterranean region. Frequently, the dominant tree species is Cypress – particularly *Cupressus sempervirens* L. (Brofas et al., 2006). The resistance of this species to drought and pollution allowed for its widespread occurrence in these specific climatic conditions (Farjon, 2005). Even though *C. sempervirens* was considered a problematic tree species for tree ring analysis in the past (Schweingruber, 2007; Ważny et al., 2014), it is occasionally used for dendroclimatic (Gholami et al., 2017) or dendroarchaeological (Lev-Yadun, 2007) reconstruction due to its high sensitivity to climate. Nevertheless, its use in dendrogeomorphology is still untested. The evaluation of the reliability of *C. sempervirens* for palaeoflood reconstruction and determination of its benefits and limits could lead to more extensive tree ring-based reconstruction of flood chronologies in selected regions of the Mediterranean.

The main aims of this study are (i) to verify the possibilities of Italian cypress (*C. sempervirens*) for palaeoflood reconstruction using dendrogeomorphic approaches, (ii) to build the chronology of past hydrogeomorphic events in two selected gorges in the eastern Mediterranean region, and (iii) to describe relationships between the character of the process and spatial distribution of affected trees.

2. Study area

The research was conducted on the island of Crete (Greece) (Fig. 1A, B), located in the southern part of the Aegean Sea. The island's elongated east-west orientation in combination with the presence of high mountain ridges when the highest peaks reach > 2400 m above sea level (a.s.l.) causes specific orographic conditions that result in the spatial diversification of precipitation. According to Koutroulis et al. (2010), the western part of the island is more prone to flooding than the rest of the island. Precipitation totals significantly increase with altitude. Mean annual precipitation in the coastal areas does not exceed 400 mm per year, whereas at the highest basin peaks, the precipitation totals can reach > 2000 mm per year (Rackham and Moody, 1996). Annual precipitation shows strong seasonality, as > 90% falls in the winter period between October and March. Snowfall usually occurs above 1000 m a.s.l. during this period (Tsanis et al., 2011). Summer downpours can also occur. Despite the presence of intermittent summer downpours, no geomorphic effect of floods has been recorded during these events (Maas and Macklin, 2002).

For our purposes, two neighbouring ungauged gorges on the southern coast and southern slopes of the Lefka Ori Mountains were selected (Ilingas; 35°13.5′ N, 24°7.2′ E and Sfakiano; 35°14′ N, 24°09′ E) (Fig. 1 C). The geology is dominated by Jurassic and Triassic crystalline limestone (IGME, 1993). The highest peaks of the basins in both gorges lie in the culmination parts of the Lefka Ori Mountains. The Ilingas Gorge has a zigzag course with several sharp changes in direction. Rock steps that are up to several metres high occur in the lower parts of the gorge. In contrast, the Sfakiano Gorge has a linear, five-kilometre-long course below the confluence of several partial source tributaries. Rockfall and colluvial taluses occur frequently along the sides of both gorges. The width of the gorge floors range from 7 to 45 m. Both gorge floors are mostly filled by sediments of various particle-size fractions (gravels to boulders), except for a few short, narrow reaches incised into the limestone bedrock. The typical fluvial channel (i.e. the active stream bed with flowing water and the banks) is mostly absent, and the subsurface flow dominates. Vegetation habitats are concentrated in the gorge floor and sides. Oleanders (*Nerium oleander* L.) are localised in the lowest parts of the gorges. Italian cypresses (*C. sempervirens*) occupy the lower and middle altitudes, and Calabrian pine (*Pinus brutia* Ten.) is in the upper parts of the basins. Two historical floods are known in the Sfakia region according to archival sources: November 1993 and December 2000 (Wilson, 2015). The serious aftermaths of the 2000 flash flood event in the Ilingas Gorge are described in the local tourist guidebooks (Wilson, 2015). Considering the occasional use of hiking trails in both gorges, there is a potential need for more precise HP chronology to inform about the flood risk for the tourist infrastructure.

3. Methods

3.1. Geomorphic mapping

The middle ca. 3.7-km-long reach of the Ilingas Gorge with an altitude range of 80–680 m a.s.l. and the middle ca. 5.5-km-long reach of the Sfakiano Gorge with an altitude range of 230–770 m a.s.l. were studied in detail (Fig. 1 C). Geomorphic mapping focused on hillslope process forms – rockfall and colluvial taluses; fluvial accumulation landforms – lateral terraces, lobes and bars; fluvial erosional landforms – gullies and erosion steps on the accumulation landforms; and geological structural landforms – structural steps and bedrock landforms. The position of the selected trees for subsequent sampling was recorded for mapping using GPS (precision 3 m) and adjusted with orthophoto images. In addition, we used data about basic morphometric and sedimentological parameters in the Sfakiano Gorge valley floor (Galia et al., 2018). These data helped to analyse the behaviour of the last high-magnitude flood in 2000 in more detail. Active floor width (i.e., relatively flat valley floor with unvegetated deposits) and valley gradient were measured at 50-m intervals along the longitudinal profile using a laser rangefinder. The areal proportion of three basic grain-size classes (gravel, pebble, and cobble) of sediments covering the active valley floor was visually estimated and recorded for each distance interval.

3.2. Field dendrogeomorphic approaches

Tree sampling exclusively focused on trees with visible damage to their stems because scars are generally considered the most relevant indicator of past geomorphic process occurrence (Stoffel and Corona, 2014). Only trees with scars in the logical orientation against the inferred flow direction were selected. This approach eliminates the noise from the possible sampling of trees wounded by rockfall or the falling of neighbouring trees. All selected trees were sampled by a Pressler increment borer (max. 40 × 0.5 cm). The position of the sampling was next to the overgrowing callus pad according to Ballesteros et al. (2015a, 2015b, 2015c) at the height of the maximal scar tangential extension. To obtain an optimal sample containing the border between an undisturbed tree ring sequence and the onset of the callus pad, it was usually necessary to extract several samples from tree individuals. This approach was selected to obtain the most reliable signal about the past HP events from the tree ring series of *C. sempervirens*. Twenty undisturbed trees growing on the stable inter-gorges plateau at an elevation of ca. 650 m a.s.l. were sampled for the construction of reference chronology. Two increment cores in the direction perpendicular to the slope were extracted from each reference tree.