TREE-RING BASED, REGIONAL-SCALE RECONSTRUCTION OF FLASH FLOODS IN MEDITERRANEAN MOUNTAIN TORRENTS

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Abstract

In small mountain catchments of the Mediterranean basin, heavy and intense rainfalls produce frequent flash floods that can cause economic damage and even fatalities in the often densely populated valley areas. To reduce future damage of such events, the application of mitigation strategies aimed at hydrological control and disaster risk reduction is essential. However, to reach this goal, flash flood frequency and magnitude need to be characterized in space and time. This task is highly challenging in areas where existing records are either lacking, short or highly incomplete. In poorly or completely ungauged catchments, tree-ring based flash flood reconstruction has proven useful to overcome this limitation and is now considered a valuable, alternative approach to extend flow records back in time. Tree-ring based reconstructions of past flash floods have been employed widely in many different geographic contexts worldwide, but were less frequently used in Mediterranean torrents, and not at all in Southern Italy so far. Here, we present a regional flash flood reconstruction from five poorly gauged mountain catchments in Calabria (southern Italy) to reconstruct both the timing and the magnitude of five extreme flash flood events of the last 60 years. We show that the return periods of these events ranged between 5 and 30 years based on hydraulic (Manning's equation) and hydrological (rational formula) approaches. Validation of the reconstructed discharge values was done by using direct water depth measurements (obtained from a gauging station). Our results suggest that the combination of different methods allows a reliable reconstruction of extreme hydrological events by easy-to-survey parameters in ungauged torrents of Mediterranean environments. We also demonstrate that tree-ring approaches have the potential to be applied in ungauged (or poorly gauged) Mediterranean mountain catchments as well so as to improve records of the frequency and magnitude of past flash flood activity.

Keywords: Paleo-stage indicators; ungauged headwater; catchment hydrology; semi-arid environment; extreme events; hydraulic approach.

1. Introduction

The small catchments of the Mediterranean semi-arid environment are repeatedly affected by intense rainfalls capable of generating high and impulsive floods (so-called "flash floods"). Although originating in remote mountain areas, the disruptive effects of flash floods often propagate to valley urban areas (Sabato et al., 2004; Bombino et al., 2007; 2008; Fortugno et al., 2017). A flash flood is defined by high amounts of rainfall leading to a very rapid (flashy) runoff in small catchments with a concentration time of few hours (Lóczy et al., 2012; Lucia et al., 2015).
In mountain streams characterized by high longitudinal gradients and concentration times of less than 2 hours, flash floods can activate high water and sediment flows (Jarrett, 1990; Borga et al., 2007; Gaume et al., 2009; Ruiz Villanueva et al., 2010; Hooke 2016). The sudden occurrence of flash floods renders the process difficult to predict and favours the occurrence of important economic and human losses (Gaume et al., 2009). Pappenberger et al. (2015) reported that flood events occurred in Europe between 2002 and 2013 caused € 54 billion of losses either by direct damage to goods and people or by indirect damage to the economic development of the affected region following such events. As a result, the European Commission has issued the Flood Directive (2007/60/EC) in 2007 in which she forces EU Member States to produce flood hazard and risk maps.

However, this task is highly challenging due to the scarcity of flow records, particularly in regions of southern and eastern Europe (Llasat et al., 2010). This lack of data often prevents proper design and implementation of catchment management strategies, such as plans for the mitigation of hydraulic risks (Enzel et al., 1993; Benito et al., 2004; Bodoque et al., 2015; Ballesteros-Canovas et al., 2019).

The reconstruction of past floods in ungauged or poorly gauged watercourses could critically assist risk mapping in areas subjected to floods of a certain magnitude (Garrote et al. 2018) and increase the knowledge of "flooding history" (in particular, dates and discharge of past extreme floods, also called "paleofloods"; Kochel and Baker 1982; Baker, 1983; Baker, 2008; Benito et al., 2003, Wilhem et al., 2018; Speer et al., 2019). In the absence of such data, any probabilistic assessment, aimed at estimating flood frequency-magnitude relations, remains difficult and poorly significant due to the lack of any observed flows.

Extreme floods typically leave traceable evidence along their course both in the riverbed where the morphology can be strongly modified and in riparian vegetation which is often damaged or even completely destroyed by the flood (Gurnell and Petts, 2003; Surian and Rinaldi, 2003; Osterkamp and Hupp, 2010; Hooke 2007). Scars on tree trunks induced by the impact of debris and wood carried by a flood can be observed frequently along the active channel of a river. These signs represent the most commonly observed botanical evidence (Yanosky and Jarret, 2002) of past flood activities and are sometimes also defined as "paleostage indicators" (PSI; Baker et al., 2002; Jarrett and England, 2002; Ballesteros et al., 2015a). PSI are fundamental for flood reconstruction as they offer reliable estimates of past flood frequency (Harrison and Reid, 1967; Gottesfeld and Gottesfeld, 1990; Zielonka et al., 2008; Ruiz-Villanueva et al., 2010) and/or magnitude (Sigafoos, 1964; Yanosky and Jarrett, 2002; Ballesteros-Canovas et al., 2011a/b), provided that a relevant approach for their survey and dating is available.

In the case of scars on trees, dendro-geomorphic approaches can be used to study interactions of torrent hydrology and morphology during the occurrence of paleofloods with riparian vegetation (Fortugno et al., 2017; Ballesteros-Canovas et al., 2015b); scars in treeshave therefore been used in different environments across the globe to reconstruct past floods, especially in Central and Northern Europe and in North America (Sigafoos and Hendricks, 1961; Sigafoos, 1964;Helley and LaMarche, 1973; Yanosky, 1982; Hupp, 1988; Jarrett and England, 2002; Stoffel et al., 2010; Ballesteros Canovas et al., 2013; Šilhán et al., 2018; Victoriano et al., 2018). By contrast, the approach has been applied much less frequently to Mediterranean torrents, and never so far in southern Italy.

In this paper, we attempt to fill this gap by reconstructing paleofloods and peak discharge in five mountain catchments (2 ungauged sites and 3 gauged sites with stream flow monitoring) of Calabria (southern Italy). This analysis represents the first attempt to apply dendro-geomorphic method in *fiumaras*, i.e. in streams that are typical of the semiarid Mediterranean environment of southern Italy. We then compare peak discharge based on dendro-geomorphic approaches with those obtained with Manning's equation (hereafter "hydraulic approach") and rational formula (hereafter “hydrological approach”). In a last step, results are validated by direct comparison to water depths measured by the available gauging stations in the three gauged catchments.

2. Study areas

The study was carried out in five mountain torrents in Calabria (southern Italy); two of these are ungauged (Gallico, hereafter “GA”; Sant’Agata, “SA”), whereas three have a significant observational record (Allaro, “AL”; Alli, “AI”; Melito “ME”), (Fig.1). The selection of the 5 catchments was guided by the presence/absence of gauging stations as well as by differences in climate, i.e. temperate at GA and AL and semiarid at SA, AI and ME. These torrents, locally called *"fiumara"*, are short, ephemeral streams subjected to abundant autumn and winter rainstorms, with subsequent flash floods mobilizing large amounts of sediments (Zema et al., 2018; Bombino et al., 2019). The headwaters of these fiumaras, representative of mountainous watercourses of Calabria and Sicily, exhibit perennial flow and steep longitudinal profiles (Fig. 2). Erosion is massive during floods and allowed the formation of deep and narrow valleys with many floodplains in the lowlands. Hillslopes are covered with well-developed riparian vegetation.

Fig. 1. Location and map of the five studied catchments with the relative land use

The SA, GA and AL torrents originate in the Aspromonte massif, whereas the AI and ME torrents have their sources on the Sila plateau. All five torrents discharge into the Ionian Sea (Table 1); their morphology can be classified as ‘alluvial cascade’ according to Montgomery and Buffington (1997). From a climatic and environmental perspective, the five catchments belong to 3 microclimatic and geographic groups: GA and SA are locate in the area of the strait of Messina and are influenced by the Tyrrhenian Sea with a hot Mediterranean climate and semiarid conditions (Csa,according to the Köppen classification), AL is influenced by the lower Ionian Sea with a warm Mediterranean climate and humid conditions (Csb), whereas ME and AI are controlled by the central Ionian Sea with a hot Mediterranean climate and arid conditions (Csa).

Table 1. Main morphometric and climatic characteristics of the five catchments.

Parameters		***Catchments***				
		Ungauged		***Gauged***		
		Gallico[1]	***S. Agata[2]***	***Allaro[3]***	***Melito[4]***	***Alli[5]***
		Morphometry				
Area (km^2)		55.5	61.0	130.34	157.44	128.33
Latitude		38°10’N	38°05’ N	38°26’N	39°03N	39°06’N
Longitude		15°47’E	15°45’E	16°21’E	16°29’E	16°30’E
Maximum altitude (m a.s.l.)		1770	1610	1407	1322	1454
Mean altitude (m a.s.l.)		704	893	713	858	708
Mean slope (%)		26	29	31	25	38
Length of main stream (km)		26	24	30	23	17
Mean slope of the main stream (%)		7.24	6.67	16	12	20
		Climate				
Annual rainfall (mm)	Mountain reach	1613	1381	1802	1242	1455
	Valley reach	763	621	963	767	798
Annual temperature (°C)	Mountain reach	9.9	11.1	11.4	9.0	9.0
	Valley reach	18.2	18.2	17.9	18.4	18.4

Notes: 1) Mountain reach: rainfall / temperature station, Gambarie - 1350 m a.s.l.; valley reach: rainfall / temperature station, Catona - 50 m a.s.l.; 2) Mountain reach: rainfall / temperature station, Gambarie - 1350 m a.s.l.; valley reach: rainfall / temperature station, Reggio Calabria - 30 m a.s.l.; 3) Mountain reach: rainfall / temperature station, Mongiana - 920 m a.s.l.; valley reach: rainfall / temperature station, Caulonia - 298 m a.s.l.; 4) Mountain reach: rainfall / temperature station, Albi -742 m a.s.l.,; valley reach: rainfall / temperature station, Catanzaro Lido - 40 m a.s.l.

Geology consists of metamorphic rocks (mostly micaschists, amphibolites, phyllites, quartzites and granitic gneisses) and Pleistocene gravels. Land use consists mostly of forest with shrublands, natural grassland and natural forests dominated by *Fagus sylvatica* L., *Abies alba* subsp. *apennina*, as well as reforestation by *Pinus nigra* ssp. *laricio*. Riparian vegetation inside the active channel is dominated by *Alnus glutinosa* L., *Alnus cordata* (Loisel.), *Salix caprea* L, *Fraxinus ornus* L. and *Popolus tremula* L., whereas the shrub layer is composed primarily by *Cytisus scoparius* L., *Cytisus villosus* and *Spartium junceum* L.

The catchments host the city of Reggio Calabria and some villages with an overall permanent population of about 190,000 (SA and GA catchments), 8,340 (AL) and 106,108 (AI and ME) inhabitants. These populations have suffered repeatedly from destructive floods in 1911, 1929, 1953, 1971, 1996, and 2000, and by more than 100 smaller events recorded in newspaper articles. Despite the number and magnitude of floods in the early 20th century, systematic and continuous measurements of flood events only started in the 1970s (Caloiero et al., 1980).

Fig. 2. Characteristic views of the mountain reaches of the Gallico (a), Sant'Agata (b), Allaro (c), Melito (d) and Alli (e) catchments.

3. Methodology

Dating of past floods and estimation of their peak discharge was undertaken through the integration of dendro-geomorphic, hydrological and hydraulic analyses (Ballesteros Canovas et al., 2011a; 2011b; Yanosky and Jarrett, 2002). To this end, the following working steps have been undertaken (Fig. 3): (i) sampling and analysis of PSIs left on trees by past floods; (ii) collection and processing of historical rainfall series; (iii) analysis of relationships between PSIs and the most important rainfall parameters; (iv) location and characterization of stable cross-sections showing PSIs; (v) peak discharge estimation using two independent hydraulic and hydrological approaches; (vi) validation of the dendro-geomorphic method in the gauged catchments.

3.1 Sampling and analysis of PSI left by past flash floods

PSIs were selected by field surveys for each section of the five headwaters. Evident PSIs used in this study includedscars, tilted trees, equally aged trees, sprouts from tilted parent trees and represent the result of the impact of rocks and wood carried by the floods (Baker et al., 2002; Benito et al. 2004). We carefully excluded marks which could have been inflicted by processes other than hydrological, such as rot, landslide, and/or rockfall (Ballesteros et al., 2011 a,b; Zielonka et al., 2008). PSIs were identified and georeferenced with a Trimble JUNO GPS.

Cross-sections of trees bearing PSI evidence, were cut from dead stumps, whereas increment cores and wedges containing scars were taken from living trees (Arno and Sneck, 1977). After species identification and positioning of trees on the map, cross-sections and wedges were transported to the lab, air dried and then polished by a belt sander (Zielonka et al., 2008). Increment cores were first glued on wooden supports, and then air-dried and polished as well. Wounds were located in the tree-ring record and dated to the year (Yanosky, 1982; Zielonka et al., 2008) with a stereomicroscope (Stoffel and Bollschweiler, 2008).To this end, we used a visual approach based on skeleton plots to crossdate the dendrochronological curves of samples taken from each PSI (Wigley et al. 1987; Fig 3).

3.2 Collection and processing of rainfall historical series

Meteorological information was collected from rainfall gauge stations located as close as possible to the torrents. The selected stations included Gambarie d'Aspromonte for GA and SA, Albi for AI and ME, and Mongiana for AL; all stations are located within the catchments for which their data was used. Rain gauge records span the period 1918–2010, from which we extracted the maximum 24-hour ($h_{max,24}$) and critical depths (h_{tc}) indicators – i.e. the rainfalls with duration equal to the catchments' concentration time (t_c) – are factors commonly used to represent the main meteorological triggers.

3.3 Analysis of relationships between the PSIs and the rainfall parameters

All PSIs detected in the field were dated so as to relate their dates with heavy rainfall events causing a flood. Moreover, the relationship between the number of PSIs, $h_{max,24}$and h_{tc} was evaluated with a linear regression analysis by selecting four timewindows, namely 1951-1965, 1966-1980, 1981-1995, and 1996-2010.

3.4 Identification and location of stable cross-sections showing PSIs

In the reaches of the investigated catchments, we identified "stable" cross-sections (i.e. section with unchanged width and depth over the years) with PSIs (Kochel and Baker, 1988; Benito and O'Connor, 2013). For each cross-section (Fig. 3), we acquired topography and bathymetry (Sigafoos 1964; Ballesteros-Canovas et al., 2011a; 2011b) with a total station (Pentax R-400) according to Zema et al. (2018) and Bombino et al. (2019). Water discharge was assumed as a slightly variable between the upstream and downstream extreme sections, due to the lack of any tributaries.

3.5 Peak discharge estimation

In the mountain reaches of the catchments, channel geometry was measured at the level of stable cross-sections and the expected maximum water depth of floods was identified with the highest PSI. On the basis of this assessment, we estimated peak discharge based on both hydraulic and hydrological approaches (Fig. 3).

In a first step, we applied the "step-backwater" hydraulic approach (O'Connor and Webb, 1988; Benito et al., 2003) in order to obtain peak flow values calculated from water depth, thereby minimising differences between PSI heights and the expected water depth estimated by HEC-RAS model (Hydraulic Engineering Center – River Analysis System, US Army Corps of Engineers, 2010). To this end, we used an iterative process to assign peak discharge whenever deviations between the modelled water depth (hereafter h_{sim}) and PSI height (hereafter h_{PSI}) of a specific flood event were minimal. Deviations were simulated considering the hypothetical impact depth of wood or cobble transported by the flood under three "flood stage" scenarios (S_{min}: minimum, S_{med}:

medium, and S_{max}: maximum) based on scar-height distributions observed on trees in the reach. These scenarios are in fact, based on the statistical distribution (S_{min} = 5th percentile, S_{med} = 50th, and S_{max} = 95th) of the observed deviations between scar heights and modelled water depths in the case that all scars were fully submerged (meaning that the related discharge is indicated as Q_{sub}; Ballesteros et al., 2011a).

In a second step, we employed a hydrological approach to estimate peak discharge from maximum rainfall depths recorded in the year to which the PSI was dated. This approach uses the most reliable value of the discharge based on the rational formula (Chow 1964; Wang et al., 2012). Hydrological models are usually used to estimate the peak discharge in cases for which flow data is not available and/or unreliable, but where precipitation data is abundant (Garrote et al., 2018). Using the critical rainfall depths recorded in a year in which PSI exist, the rational formula can thus be employed to estimate maximum discharge in the catchment. The return period (T=15 years) was calculated with the empirical frequency of exceedance of 4 extreme rainfall events according to Weibull-Hazen and Gringorten methods (Weibull, 1951; Hazen, 1914; Gringorten, 1963). The empirical distribution frequency was then compared to the EV1 Gumbell law of extreme values distribution type 1 for h_t= t_c and h_{max}=24h. Precipitation records for the calculation of h_{tr} were collected at the rain gauge stations listed above, using a 30-year historical series of 1, 3, 6, 12, and 24-hour maximum rainfall.

Topographic information needed to calculate catchment area was derived from a 1-m resolution DEM provided by the Italian Ministry of Environment.Runoff coefficients were estimated as the weighted average of the individual C of each area with homogenous land use, soil texture, and slope (Grillone et al., 2014). In a final step, we compared peak discharges as obtained by the different independent approaches.

Fig. 3. Methodological flowchart used for reconstructing of peak discharge during past flood events based on palaeostage indicators (PSIs) and damage in trees in stable cross-sections (h_{PSI} = scar heights; h_{SIM} = HEC-RAS simulated water depth; Sn_x= scenarios 1, 2, and 3; Q_{max}= max. discharge calculated with the rational formula).

3.6 Validation of estimated peak discharges

In the catchments of the AL, ME and AI torrents, direct measurements of a flood are available for the event that occurred on December 31, 1972 and January 1, 1973 from the Regional Agency for Environment Protection of Calabria (ARPACAL). These measurements were used for validation of the different methods (Fig.4). We also checked for correspondence between the date of the 1972-73 flood and the age of the PSIs identified in the catchments.

PSIs heights were then compared with measured water depths. Statistical significance of differences between mean PSI heights and water depths were analysed with the Shapiro-Wilk test (at p level <0.05). To this end, we first applied the Shapiro–Wilk test to determine whether the population from which the samples originated followed a normal distribution (i.e., standardized kurtosis and standardized skewness).

Moreover, for each cross-section containing PSIs, topography and other characteristics such as bed sediment grain size and vegetation were measured. A 1-m DEM of entire catchments was derived from LiDAR data so as to improve the reliability of topographic surveys. Finally, historical discharges of sampled floods were simulated with HEC-RAS. On the basis of the water levels related to historical discharges (obtained by simulating past floods within the channel), average widths of the cross-section were calculated in order to assess possible cross-section geometry changes that might have occurred over the years.

Fig. 4. Methodological flowchart used for the validation of dendro-geomorphic method (h_{SIM} = HEC-RAS simulated water depth; Q_{max} = Max discharge calculated by rational formula)

4. Results and discussion

4.1 PSIs characterization and rainfall series processing

In the sub-reaches of the GA, SA, AL, AI and ME mountain catchments, a total of 55 stable cross-sections were identified with ample evidence of past floods recorded in trees. Within these sections, 107 (GA), 123 (SA), 10 (AL and AI, respectively) and 8 (ME) trees showed PSIs that could be linked to the impacts of rocks and woody material transported by past floods;a majority of PSIs were found in *Alnus cordata,Alnus glutinosa,Salix caprea* and *Fraxinus ornus* trees. For sequencing

PSIs a cross dating technique was carried out in the five studied catchments. A total of six sequences were found and an example is reported in the Figure 5.

Fig. 5. A sequences carried out by cross-dating technique applied in the five studied catchments

The dates of the highest $h_{max,24}$and h_{tc}observed in the observation period (1951-2010) were then compared with the dates of PSIs. The values obtained in years exhibiting the largest number of flood marks (1971, 1972-73, 1996, 2000 and 2003) were then matched with maximum values (or extreme events) seen in the hydrological variables (Fig. 6a, b and c).

Fig. 6.Rainfall depth (dashed and full lines are for $h_{max,24}$ = 24-hour maximum rainfall depth and h_{tc} = critical rainfall depth value, respectively) and number of PSIs (bars) left by floods in reaches of the (a) Gallico, (b) Allaro and (c) Alli /Melito catchments. Light grey bars highlight the extreme events of 1971,1972-73, 1996, 2000, and 2003.

A positive, but low correlation (r^2 = 0.12 for GA, r^2 = 0.37 for SA) was found regressing the number of PSIs against the annual values of h_{tc} during the observation period (Fig. 7 - for simplicity, Figures7, 8 and 9 show three representative catchments, G, for the area of the Strait of Messina, AL, for the lower Ionian Sea, and AI, for the central Ionia Sea). To identify partial temporal trends, the entire period was split into 15-year time windows (1951-1965, 1966-1980, 1981-1995 and 1996-2010). High coefficients of determination were only found for the time window 1996–2010 (r^2 = 0.63 for GA, 0.86 for SA, 0.88 for AL, 0.81 for AI, and 0.92 for ME, respectively) (Fig. 7). By contrast, minimum values were found in the early period 1951–1965; (r^2 = 0.10 for GA, 0.40 for SA, 0.30 for AL, 0.35 for AI, and 0.09 ME, respectively) (Fig. 7 8); this finding can likely be explained by the lower probability to observe visible scars as one goes back in time. It is therefore, possible that we miss some events in the 1950s, which can influence correlation analyses between paleoflood and precipitation time series (Ballesteros Canovas et al. 2018; Stoffel et al., 2013). The coefficients of determination were slightly higher compared to those estimated for h_{tc}, provided that the number of PSIs was correlated to h_{max24}recorded for each year (r^2 = 0.49 for GA, 0.64 for SA, 0.33 for AL, 0.50 for AI, 0.36 for ME, respectively) for the period 1951–2010. In this case, r^2 values of the four time windows progressively increased from 1951 to 2010 (r^2 = 0.02 for GA, 0.01 for SA, 0.38 for AL, 0.13 for AI, and 0.80 for ME, respectively for the period 1951–1965 as compared to r^2 = 0.74 for GA, 0.87 for SA, 0.67 for AL, 0.63 for AI, and 0.63 for ME, respectively for 1996–2010) (Fig. 7 8).

Fig. 7. Linear regressions between the number of PSIs and critical rainfall depth (h_{tc}) measured in the Gallico, Allaro and Alli torrents for the time windows 1951–1965 and 1996–2010.

Fig. 8. Linear regressions between the number of PSIs and maximum 24-hour rainfall depth (h_{max}) at Gallico, Allaro, and Alli torrents for the time windows 1951–1965 and 1996–2010.

4.2 Step-backwater and rational methods application

The estimation of peak discharge based on PSIs requires an *ex-ante* calculation of a peak discharge that submerges all scars (Q_{sub}; Ballesteros-Canovas, 2011a; 2011b). For the events of 1996, 2000, and 2003, Q_{sub} values were in the range of 70.2–96.3, 25–50, 15–67, 11.4–34, and 14–41 $m^3 s^{-1}$ for the GA, SA, AL, ME and, AI catchments, respectively (Fig. 9a–c). In line with Gottesfeld (1996), Yanosky et al. (2002) and Ballesteros-Canovas et al. (2011a; b), we hypothesize that PSIs can be located above or below the estimated flood level (Q_{sub}), such that, the use of a single value for the reference value of Q_{sub}, can be questioned because scars can be inflicted to trees above (in the case of woody debris) or below (rocks) the actual water table. The minimum peak discharge that submerged all PSI (Q_{sub}) ranged between 19 and 32 $m^3 s^{-1}$ for SA and between 15 and 28 $m^3 s^{-1}$ in the case of GA. In the case of AL, ME, and AI, values were 30, 35, and 70 $m^3 s^{-1}$,respectively. Based on the aforementioned, we considered that water depth can be above (maximum scenario) or below (minimum scenario) the actual flow level (Ballesteros et al., 2011a)

Fig. 9. Estimation of peak discharge submerging all PSIs (Q_{sub}) as obtained with a step-backwater approach for the extreme floods that occurred in 1971, 1996, 2000, and 2003 in the Gallico (a) and in 1972-73 in the Allaro (b) and Alli (c) torrents.

Deviations between PSI heights measured in the field and estimated flood depths were calculated for the minimum, medium, and maximum scenarios for an expected discharge range for the extreme floods of 1971, 1972-73, 1996, 2000, and 2003. The discharge variability between the $S_{min}$and S_{max} scenarios (Table 2) was generally smaller than 10%. These calculations also provided the most reliable peak discharge value, which, according to Ballesteros-Canovas et al. (2011a), was the minimum value (defined by S_{med}, or the 50th percentile of the distribution of PSI deviations) of the deviation for this range (Figs. 10-11). The estimated peak discharges had a return interval of 5–30 years (Table 2).

Fig. 10. Estimation of the most reliable peak discharge value (calculated for the three scenarios, S_{min}, S_{med} and S_{max}, of the step-backwater method) of extreme floods in Gallico torrent.

Fig. 11. Estimation of the most reliable peak discharge value (calculated for the three scenarios, S_{min}, S_{med} and S_{max}, of the step-backwater method) of the flood of 1971-7972 for the Allaro and Alli torrents.

The reliability of this approach was checked by comparison with peak discharge values as obtained with the rational method. We realize that differences between the approaches were negligible overall (<6%), which supports the suitability of the dendro-geomorphic approach for reconstructing peak discharge in small mountain catchments further (Table 2). Deviations between scar heights and the water depth were between -0.05 and 1.27 m. A total of fourteen scars (50% of all cases) were within a deviation of ±0.2 m with an average deviation of scars of 0.14 m. Values obtained in this study are comparable to those reported by Yanosky and Jarrett (2002), who found that almost half of their scars were within ±0.2 m. In the case of the AL, ME and AI torrents, deviations between PSI heights and simulated flood water depths for the three scenarios were smallest for the following range of peak discharges: 10–100 $m^3 s^{-1}$ (AL), 20–100 $m^3 s^{-1}$ (ME), and 40–150 $m^3 s^{-1}$(AI) (Fig. 11). For the S_{med} scenario, peak discharges corresponding to the minimum deviation are 26 $m^3 s^{-1}$ (deviation of 1.9%; variance of 0.4 m, AL catchment), 55 $m^3 s^{-1}$ (deviation of 2.4%; variance of 0.60 m, ME), and 80 $m^3 s^{-1}$ (deviation of 1.9%; variance of 0.6 m, AI). Peak discharge of the flood that occurred in 1972 can be estimated in a range from 20–80 $m^3 s^{-1}$ with an average deviation of 2.6% for the three gauged catchments (Table 2).

The noticeable presence of PSIs in the upstream reaches of the GA and SA *fiumaras* (and somewhat less in AL, ME and AI) allowed dating the occurrence of extreme past floods and estimation of their magnitude. It is well known that floods with a certain discharge may damage trees (due to the impact of the material carried by the flow) and, in some upstream reaches, noticeably change, besides channel morphology, riparian forest stand structures; as was the case at our study sites (Bombino et al., 2009; 2014). Availability of historical series of heavy precipitation events allowed correlating PSI age with occurrence years, during which heavy rainfalls presumably generated the largest floods. In the investigated catchments, a large number of PSIs was detected in juvenile trees; thereby confirming the unsteady equilibrium of riparian environments where large spatial and temporal variability of hydrological and related geomorphic processes cyclically alters riparian ecosystems, with subsequent regrowth.

Table 2. Peak flow estimation for the three scenarios (S_{min} , S_{med} and S_{max}) as obtained with the step-backwater and rational methods for the Gallico (GA), Sant'Agata (SA), Allaro (AL), Melito (ME), and Alli (AI) torrents.

		Step-backwater method					**Rational method**
Year	*Catchment*	S_{min}	S_{med}	S_{max}	T_d	T_d/T_r	
		Q (m^3 s^{-1})			*(years)*	*(-)*	*Q (m^3 s^{-1})*
1971	S. Agata	45	45,8	46,3	10	2	48,2
	Gallico	70,2	70,4	71,2	20	1	79,5
1972	Allaro	25,5	26,0	27,0	5	1	27,7
	Melito	53,0	55,0	58,0	10	1	55,2
	Alli	74,0	80,0	88,0	30	1	84,6
1996	S. Agata	35,9	40,8	41,4	10	2	40,6
	Gallico	85,2	85,7	85,9	30	0,8	87,2
2000	S. Agata	75,2	75,8	76,3	20	0,7	81,5
	Gallico	95,2	95,8	96,3	30	0,4	100,3
2003	S. Agata	50,3	55,1	55,0	10	1	65,2
	Gallico	80,0	80,7	81,9	30	1	83,7

Note: Tr = return interval of rainfall; Td = return interval of peak discharge.

In the catchments investigated here, a total of 20, 16, 5, 6, and 8 stable cross-sections were surveyed at GA, SA, AL, ME, and AI catchments, respectively. Regarding flood reconstruction, comparison of flood peak discharge values as calculated with the hydraulic approach at stable cross-sections with those modelled by HEC-RAS and based on the h_{PSI} yielded very similar values with only very small differences between the approaches. Moreover, the reliability of these estimations was confirmed further by the hydrological approach in which peak discharge was calculated from critical rainfall depth. Similar results were obtained by Ballesteros et al. (2011a), who combined hydrological and hydraulic models to define different flood hazard scenarios in a catchment of the Spanish Central System. We thus confirm the transferability of the proposed methodology to the *fiumaras* of the Mediterranean semi-arid environment.

4.3 Validation of the dendro-geomorphic method and channel morphology evolution

Table 3 reports water depth values measured in the three gauged catchments and related peak discharge derived from these measurements. Comparison of these peak discharge values and mean PSI height was based on 27 scars located in the vicinity of the gauging stations (upstream or downstream); the differences between the mean height of surveyed (h_{PSI}) and measured flood water depth at the gauging stations were significant in the case of the AL catchment ($p < 0.05$), but not ($p > 0.05$) at AI and ME according to the Shapiro-Wilk test.

Table 3.Water depths measured in Allaro, Melito and Alli torrents and related peak discharges calculated from these values (flood event of 1971-1972).

Catchment (location of the stream gauge)	**Area (km^2)**	**Measured water depth (m)**	**Measured peak discharge ($m^3 s^{-1}$)**	**PSI height (mean ± std. dev.; number) (m)**
Allaro (Mongiana)	11.8	2.47	22	2.41 ±0.16 (n = 10)
Melito (Olivella)	11.2	2.29	49	2.54 ± 0.05 (n = 8)
Alli (Orso)	46.0	2.49	74	2.47 ± 0.09 (n = 10)

(*) Data from V.A.P.I. (Versace et al., 1989).

Differences between h_{PSI} and measured flood water depth (dH) increase with the rising distance of trees from the thalweg (Fig. 12). Overall, we find correlations of $R^2>0.50$ between h_{PSI} and h_{SIM} for the flood of 1971-1972.

Fig. 12. Linear regressions between: i) dH and tree distance from thalweg (upper charts) and ii) h_{PSI} and h_{SIM} (lower charts) for the Allaro and Alli torrents. (dH=differences PSI height; $h_{PSI=}$ PSI height; h_{SIM} = water depth simulated by the HEC-RAS model)

Comparison of water depths simulated by HEC-RAS (h_{sim}) and PSI heights (h_{PSI}) surveyed in each of the 19 cross-sections shows an average difference of +0.20 m (AL), +0.23 m (ME) and +0.41 m (AI). Negative differences (that is, $h_{sim}<h_{PSI}$) occurred in seven out of ten (AL), one out of eight

(ME) and three out of ten (AI) cross-sections. These differences were small (<0.10 m) in 39% of the cases (i.e. 11 cross-sections). With regards to torrent location, the largest vertical differences in section depth were found at AL (with variations of about 1.2 m), whereas the smallest differences were observed at AI (with variations <0.9 m). At AL torrent, the thalweg also shifted towards the channel banks. The cross-section geometry of the sections studied in the other torrents did not show appreciable vertical or lateral adjustments, apart from a slight erosion of the banks.

The methodology proposed by Ballesteros et al. (2011a, b) allows estimation of past flood discharge and the dating of events in ungauged headwaters of *fiumaras* based on PSIs left on trees and through the processing of related water depths by hydraulic and hydrologic models. Application of a hydraulic approach (i.e., the step-backwater method proposed by O'Connor and Webb, 1988 and Benito et al., 2003) in the absence of flow meters recording water depths of floods (as is the case in virtually all *fiumaras* of Southern Italy) is verified with an independent hydrological approach, that is the rational method to estimate peak discharge without hydraulic parameters.

The statistical analysis showed non-significant differences between mean h_{PSI} and the water depths measured during the 1972-1973 flood in two (AI and ME) out of three catchments. The exception is the AL catchment. Here, many trees are located far from the thalweg (only 70% of all trees with scars are within 10 m from the thalweg whereas this was the case in 90% of all sampled trees at AI and ME). Furthermore, the longitudinal axis of the current channel at AL obviously shifted and is no longer at the location where it was at the start of the 1972-73 flood. By modeling the hydraulic effects of the 1972-73 flood, the correlation between water depths and h_{PSI} on trees is evident, and thus provides an explanation (in terms of morphological changes) for the lower correlation found in this case. Moreover, surveys in the gauged catchments could not be realized in stable cross-sections. In other words, we had to hypothesize that channel geometry did not change over time, therefore assuming that floods routed along the channel under the same conditions as currently. Differences detected between simulated water depth and PSI heights may be due just to the change in the shape and size of the channel over time by spatially heterogeneous erosion and deposition processes (Gharbi et al., 2016).

5. Conclusions

In the small mountain catchments of southern Italy, the absence of instruments measuring stream flows renders the reconstruction of extreme past floods a very difficult task which also hampers the development of strategies aimed at forecasting, controlling and mitigating hydrological risks. To fill this gap, we adapted existing methodologies in the fields of dendro-geomorphology to estimate the frequency and magnitude of past extreme floods in two ungauged mountain catchments of Calabria, where these methodologies have never been validated. The application of this methodology allowed estimation of occurrence dates and peak discharge of five events that occurred over the last 60 years and that have return intervals ranging from 5 to 30 years. The use of two different approaches (i.e. hydraulic and hydrological) to simulate peak discharges within stable cross-section is seen here as a very useful aid to validate reconstructed estimates. The reliability of these estimations was checked further by an independent technique by using a common hydrological approach. A comparison of data showed the close agreement of results between the different approaches, which is promising for future research. Further validation of the dendro-geomorphology was realized in three catchments equipped with flow meters and results show a good correlation between modelled water depth and PSI heights as well. Thanks to these findings, a better understanding of channel morphological changes has been achieved. These additional results, coupled with past achievements, have proven that dendro-geomorphic techniques may be applied in small and ungauged mountain catchments with peculiar climatic and geomorphic characteristics of the Mediterranean environments as well, and therefore open new doors for further research in a hitherto underrepresented region.

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