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CHECK DAMS, RIPARIAN ECOSYSTEM EVOLUTION AND HYDROLOGICAL PROCESSES: RECONSTRUCTION OF EXTREME FLOODS IN UNGAUGED HEADWATERS OF MEDITERRANEAN ENVIRONMENT

PH.D. THESIS

Ph.D. Tutor
Prof. Santo Marcello Zimbone

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Ph.D. Candidate
Ing. Daniela D'Agostino

____

Ph.D. Co-Tutor
Prof. Giuseppe Bombino

____

Ph.D. Coordinator
Prof. Marco Poiana

____

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A conclusione del mio corso di dottorato, sento il dovere e soprattutto il piacere di ringraziare coloro che mi hanno accompagnata e sostenuta in questo percorso, con i loro insegnamenti, i loro consigli e il loro affetto.

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Check dams, riparian ecosystem evolution and hydrological processes: reconstruction of extreme floods in ungauged headwaters of Mediterranean environment

Ing. Daniela D'Agostino (daniela.dagostino@unirc.it)
Department AGRARIA, University "Mediterranea", Reggio Calabria, Italy
Tutor: Prof. Santo M. Zimbone

Briglie, evoluzione dell'ecosistema ripale e processi idrologici: ricostruzione di piene estreme in bacini montani non strumentati dell'ambiente Mediterraneo

ABSTRACT

The evaluation of the effects of anthropic interventions, such as e.g. the check dams, on channel hydrology, geomorphology and riparian vegetation characteristics has been extensively treated in the literature, although with a qualitative approach. Recently, methodologies to quantify these effects were developed, validating them on study cases in Calabria (southern Italy). In particular, within the homogeneous torrent zones a sample of check dams was selected. Two transects have been identified near each check dam (immediately upstream and downstream) and a third was located at a distance from the manufact so as to be representative of the "natural" conditions of a riverbed (control). The evaluation of the effects of the check dams, carried out by comparing synthetic indicators based on physical and vegetation parameters, detected in the selected transects, was integrated by applying statistical techniques. In particular, the analysis showed a high linear correlation between the physical indicators (section shape, profile slope, specific discharge, surface and subsurface size of the riverbed) and the vegetational ones (development, structure and biodiversity) (Zema *et al.*, 2018). In addition, investigations conducted by Bombino *et al.* (2019) allowed to reduce the number of several factors that influence the interaction between the manufacts and riparian vegetation.

The in-depth study until now described has highlighted, in particular, the need to characterize the flash floods that can affect the riparian ecosystem evolution. The current arrangement of the ecosystem, in fact, represents a "snapshot" of the riparian vegetation characteristics (in terms of organization, structure and biodiversity) near the check dams, observed at the time of the survey. It is affected not only by the interaction with the manufacts but also by the hydrological processes that take place in the headwaters. Especially, as is known, the flash floods with longer recurrence intervals can lead to drastic changes in the river environment and, often, cause the reset of plant formations,

keeping the ecosystem in a perennial condition of *non-equilibrium*. In ungauged catchments (a recurring circumstance in most Calabrian mountain catchments) it is not possible to have information about the floods frequency and magnitude, therefore it is necessary to resort to indirect methods for their estimation. In this regard, the reconstruction of flash flood events by applying the dendrochronological method has proved to be a useful tool to compensate for the lack of hydrological data and is now considered a valid approach for flood reconstruction. It is known, in fact, that the passage of an extreme flood leaves a trace on the plants (PSIs, Paleo Stage Indicators) and on the riverbed. Therefore, it is possible to date and characterize these "signs" (e.g. scars on trees trunks), whose heights is approximately indicative of a water depth. The dendrochronological approach, mainly applied in environments of central and northern Europe and North America, was applied for the first time in a semi-arid Mediterranean environment, in the case of Calabrian *fiumaras*.
In this thesis work, the results of the reconstruction of five flood events, which occurred in the last 60 years in five ungauged catchments of Calabria, are presented, defining their timing and magnitude.
Validation of the reconstructed discharge values was done by using direct water depth measurements (obtained from direct measurement). The results suggest that, even in ungauged torrents of the Mediterranean environment, the combined use of different approaches (hydraulic and hydrological) allows a reliable reconstruction of extreme hydrological events the use of easily detectable parameters, and that the tree-ring based approaches is potentially applicable 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.

RIASSUNTO
La valutazione degli effetti degli interventi antropici, quali, ad esempio le briglie, su idrologia, geomorfologia dell'alveo e caratteristiche della vegetazione ripariale è stata ampiamente trattata in letteratura, seppur con un approccio qualitativo. Recentemente, sono state messe a punto metodologie per la quantificazione di tali effetti, validandole su casi studio in Calabria (Italia meridionale). In particolare, all'interno di tronchi di corso d'acqua omogenei, è stato selezionato un campione di briglie. In prossimità di ciascuna briglia (immediatamente a monte e a valle) sono stati indentificati due transetti (fasce trasversali di alveo); un terzo è stato invece ubicato a distanza dal manufatto, in modo da

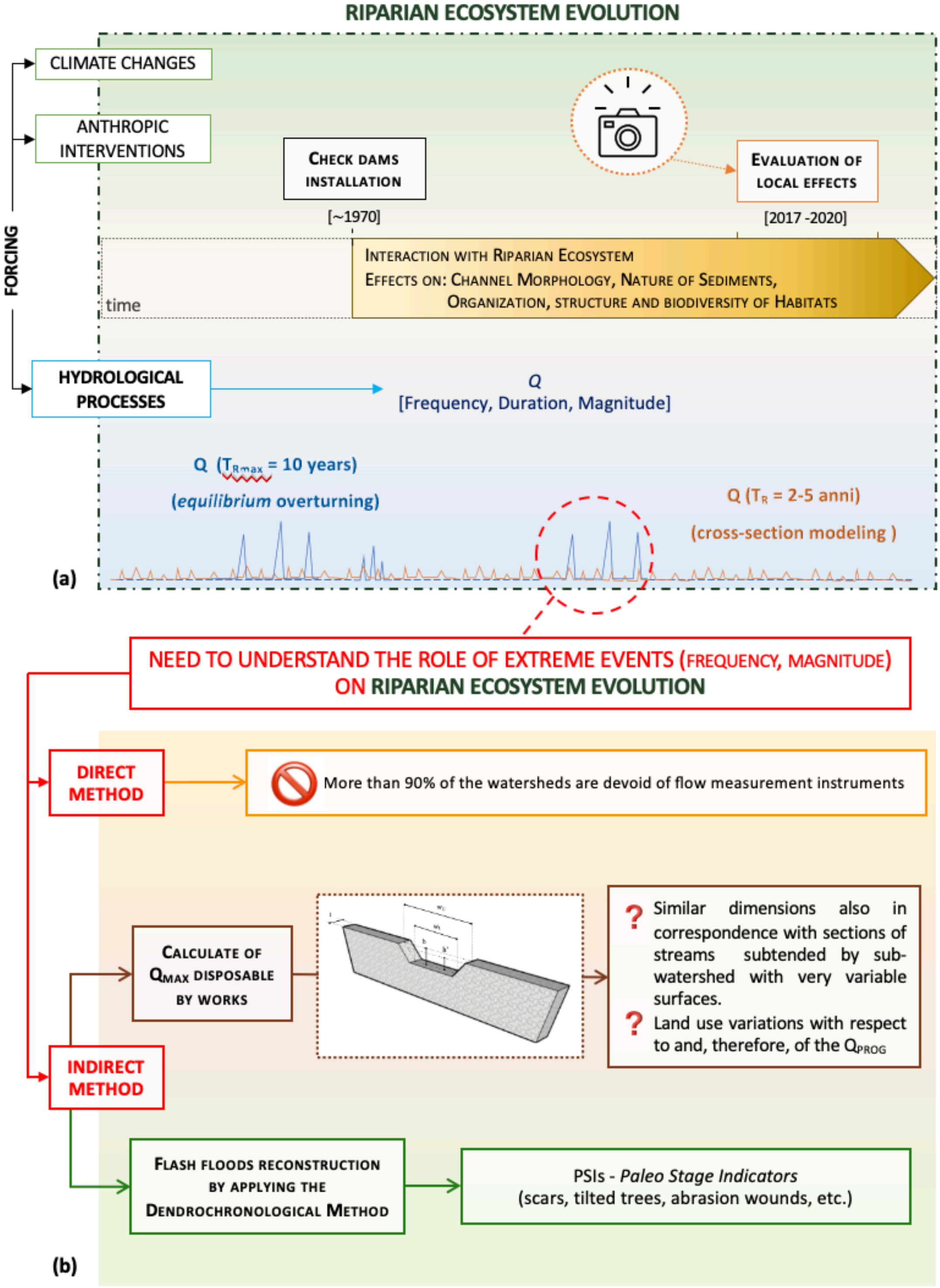
risultare rappresentativo delle condizioni “naturali” di un alveo (controllo). La valutazione degli effetti delle briglie, effettuata confrontando indicatori sintetici determinati sulla base dei parametri fisici e vegetazionali rilevati nei transetti selezionati, è stata integrata mediante l’applicazione di tecniche statistiche. In particolare, l’analisi ha mostrato un’alta correlazione lineare tra gli indicatori fisici (forma della sezione, pendenza del profilo, portata specifica, dimensioni dei sedimenti superficiali e sotto superficiali del letto del fiume) e quelli vegetazionali (sviluppo, struttura e biodiversità) (Zema *et al.*, 2018). Inoltre, indagini condotte da Bombino *et al.* (2019) hanno permesso di discriminare l’influenza dei diversi indicatori, riducendo, così, il numero di fattori che influenzano l’interazione tra i manufatti e la vegetazione ripale.

Lo studio approfondito fin qui descritto, ha evidenziato la necessità di caratterizzare le portate di piena che possono condizionare l’evoluzione dell’ecosistema ripale. L’attuale assetto dell’ecosistema fluviale, difatti, rappresenta una “istantanea” delle caratteristiche della vegetazione ripale (in termini di organizzazione, struttura e biodiversità) in prossimità delle briglie, osservate al momento della rilevazione. La formazione vegetale rilevata, in effetti, risente non soltanto dell’interazione con il manufatto, ma anche dei processi idrologici che hanno luogo nei tronchi montani dei corsi d’acqua. Soprattutto nei bacini con risposte idrologiche impulsive, come è noto, le portate di piena con elevato tempo di ritorno possono comportare drastici mutamenti dell’ambiente fluviale e, spesso, determinare il completo azzeramento delle formazioni vegetali, mantenendo l’ecosistema in una perenne condizione di *non-equilibrium*. Nei bacini privi di strumenti di misura delle portate (circostanza peraltro ricorrente nella maggior parte dei bacini montani calabresi) non è possibile avere informazioni circa la frequenza e la magnitudo delle piene, pertanto appare necessario il ricorso a metodi indiretti per la loro stima.

A tal proposito, la ricostruzione degli eventi di piena improvvisi mediante l’applicazione del metodo dendrocronologico si è dimostrata un utile strumento per sopperire alla mancanza di dati idrologici ed è oggi considerata un valido approccio per la ricostruzione delle piene. È noto, infatti, che il passaggio di una piena estrema lascia una traccia sulle piante (PSIs, Paleo Stage Indicators) e sull’alveo. Pertanto, risulta possibile datare e caratterizzare tali “segni” (ad esempio ferita da abrasione sui tronchi), la cui posizione sulla pianta è approssimativamente indicatrice di un’altezza idrica. L’approccio dendrocronologico, prevalentemente applicato in bacini dell'Europa centrale e settentrionale e del Nord America, è stato per la prima volta applicato in ambiente semi-arido mediterraneo, al caso delle fiumare calabresi.

In questo lavoro di tesi, vengono presentati i risultati della ricostruzione di cinque eventi di piena, occorsi negli ultimi 60 anni in cinque bacini montani scarsamente strumentati della Calabria, definendone la collocazione temporale e la magnitudo. La validazione dei valori di portata ricostruiti è stata effettuata confrontandoli con i relativi tiranti idrici (i cui dati sono stati ottenuti da misurazione diretta. I risultati suggeriscono che, anche in torrenti non strumentati dell'ambiente mediterraneo, l'uso combinato di diversi approcci (idraulico e idrologico), consente una ricostruzione affidabile di eventi idrologici estremi mediante l'impiego di parametri facilmente rilevabili. Si è dimostrato, inoltre, che l'approccio dendrocronologico è potenzialmente applicabile in bacini montani non (o scarsamente) strumentati dell'ambiente Mediterraneo, nonché identificare con maggiore precisione la frequenza e la magnitudo degli eventi di piena del passato.

GRAPHICAL ABSTRACT



KEYWORDS

Mountain stream; flash floods; channel morphology; transect; riparian habitat; biodiversity; bed sediment; paleo-stage indicators; water depth; non-equilibrium condition

INTRODUCTION

STATE-OF-THE ART

The Mediterranean environment is characterized by specific local conditions, such as frequent and intense rainstorms, small basins and steep slopes (Bombino *et al.*, 2007; Zema *et al.*, 2014; Rago *et al.*, 2017). Specifically, headwaters, in response to this peculiar climatic, hydro-geomorphological conditions and hydrological conditions, are prone to high magnitude flash floods which, because of their high erosive power, often causing hydro-geological instability and destruction or serious damage to urban and rural areas (Fortugno *et al.*, 2017).

In this context, (such as in Southern Italy and Spain, as reported for instance by Boix-Fayos *et al.*, 2007, and Bombino *et al.*, 2007) the management and mitigate the hydro-geological risk has often forced local administrations to fund public works over the last 60–70 years for soil conservation strategies (Zema *et al.*, 2018). About that, our attention has focused on the Calabria region the southern of the Italian peninsula, which is strongly subject to high environmental risks. Specifically, in the second half of twentieth century, some extremes events occurred in Calabria, during which the rains showed extraordinary characteristics in terms of both intensity (up to 160 mm/h) and duration (up to 535 mm in 24 hours). Some of the dramatic and disrupting episodes occurred between 1935 and 1973, where flash floods mixed to debris, moved rapidly downstream and propagated in valley urban areas (Sabato and Tropeano, 2004; Bombino *et al.*, 2007, 2008; Fortugno *et al.*, 2017), became a powerful liquid-solid mass which broke or destroyed many settlements and bridges, making hundreds of victims and forcing many people to abandon definitively their many villages, strongly damaged or completely destroyed (Caloiero and Mercuri, 1980; Versace *et al.*, 1989; Sorriso-Valvo & Sylvester, 1993; Sabato and Tropeano, 2004; Terranova *et al.*, 2016). In response to this state of emergency, National Government in the years 1953 and 1955 had issued Special Laws for Calabria region (Laws n. 938/1953 and 1177/1955): expensive investments funded a program of protection works aimed both at mitigating river floods and reclamation of swampy areas (Ruini, 1913; Acerbo, 1937; Medici, 1954; Bevilacqua, 1987).

Hundreds of kilometres of embankments, about 150,000 ha of reforestation and several thousands of check dams have been made according to an integrated approach to the basin scale (A.FO.R., 1998), in order to stabilize the longitudinal bed profile by graded sub-reaches (with a longitudinal slope lower than the original profile) and consolidating torrent banks from lateral erosion (Fortugno *et al.*, 2017). In many of Calabrian watersheds, there are up 6 check dams per km^2 (e.g. in the Molaro *fiumara*) and up to a third of the length of the main stream is delimited by embankments (for example in the case of Sant'Agata *fiumara*) (Bombino *et al.*, 2003).

Check dams are often used in Mediterranean areas (Castillo *et al.*, 2007; Boix-Fayos *et al.*, 2008; Bombino *et al.*, 2009; Quiñonero-Rubio *et al.*, 2016) with the aim of controlling sediment transport (Conesa García, 2004; Catella *et al.*, 2005; Conesa-García *et al.*, 2007) and stabilizing slopes and torrential channels (Conesa García, 2004; Conesa-García *et al.*, 2007; Nadal-Romero *et al.*, 2008), by storage of small sediment and to add flow resistance reducing channel slope and increasing roughness. They are generally built-in staircase like sequences of cemented, boulder, or wooden grade-control structures (Lenzi & Conesa-García, 2013; Zema *et al.* 2018). As a result, the studied check dams were completely silted up and their sediment storage capacity is now depleted; at present they show well-developed sediment and scour wedges (Zema *et al.*, 2014). In spite of the extreme floods occurred in the last 60 years, no disruptive effects (due to water and sediment transport downstream) on valley zones were recorded in the four regulated watersheds; conversely, in the flood of 1951 (immediately before check dam installation) entire villages were destroyed with some fatalities (Fortugno *et al.*, 2017).

The installation of manufacts have short (following a few events) and long term (related to their functioning) effects in the time. After construction, a volume of sediment is progressively trapped behind retention check dams, until the formation of a sedimentary wedge (immediately upstream of structure) having the ultimate (equilibrium) bed slope. When check dams are fully operational, they control water and sediment fluxes along stream channels, reducing hydrologic connectivity and the contribution of solid material downstream (Conesa García, 2004; Conesa-García *et al.*, 2007).

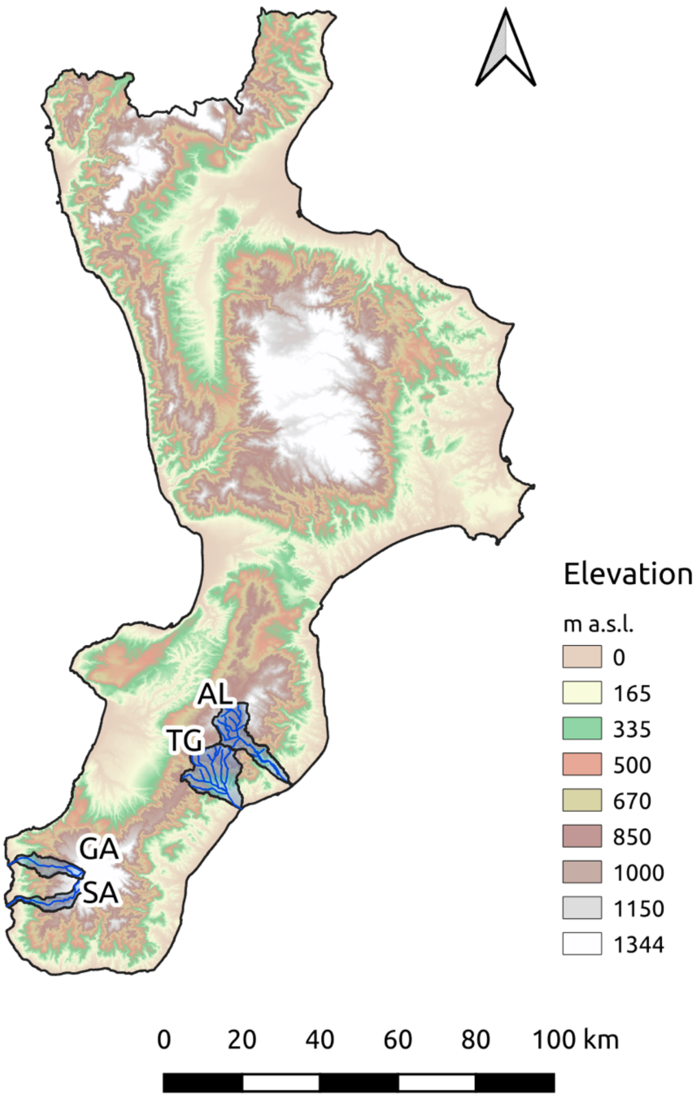
The installation of check dams modifies and influences the natural evolutionary processes and the hydro-morphology and eco-hydrology of torrents (for instance decreasing the longitudinal profile slope, thus slowing water and sediment movement along stream channels (Bombino *et al.*, 2009). All this involves local effects, such as the variation of the transversal section form, effects on surface and subsurface sediments and, then, effects on the structure and cover of riparian vegetation and even on its biodiversity (Boix-Fayos *et al.*, 2007; Castillo *et al.*, 2007; Conesa-García & García-Lorenzo, 2009; Bombino *et al.*, 2014; Ramos-Diez *et al.*, 2016b, 2017a, 2017b).

There is extensive literature on the repercussions of engineering hydraulic works: Niiyama, 1987; Nilsson *et al.*, 1991; Panetta e Hopkins, 1991; Pysek e Prach, 1993; Décamps e Tabacchi, 1994; Dynesius e Nilsson, 1994; Petts, 1984; Nilsson e Jansson, 1995; Aruga *et al.*, 1996; Stanford *et al.*, 1996; Englund *et al.*, 1997; Maekawa e Nakagoshi, 1997; Toner e Keddy, 1997; Bravard *et al.*, 1999; Andersson *et al.*, 2000; Masahito e Nakagoshi, 2001; Pedroli *et al.*, 2002; Bockelmann *et al.*, 2004, and more recent such as, e.g., Norman *et al.*, 2016; Guyassa *et al.*, 2017 on hydrology; Boix-Fayos *et al.*, 2007; Fortugno *et al.*, 2017; Gao *et al.*, 2016 on morphology; Ramos-Diez *et al.*, 2016a, 2016b, 2017a, 2017b on sedimentary effects; e.g. Bombino *et al.*, 2006, 2008, 2009, 2014 on riparian vegetation characteristics. Nevertheless, the actual impact of check dams as well as their effects on physical processes and vegetation characteristics have often been studied disjointedly by qualitative approach based on field observations (Zema *et al.*, 2018). In order to fill this gap, recent research activities have focused on methods for the quantitative evaluation of the effects of the works on the structure and distribution of riparian vegetation, also in relation to the multiple factors (biotic and abiotic), variable in space and time, which condition the organization species in plant complexes. Specifically, methodologies to evaluate the local effects induced by engineering hydraulic works were developed: on transversal works (Bombino *et al.*, 2003, 2006), on longitudinal works (Bombino *et al.*, 2007), and on the riparian vegetation (Bombino *et al.*, 2008, 2019, 2014; Zema *et al.*, 2018).

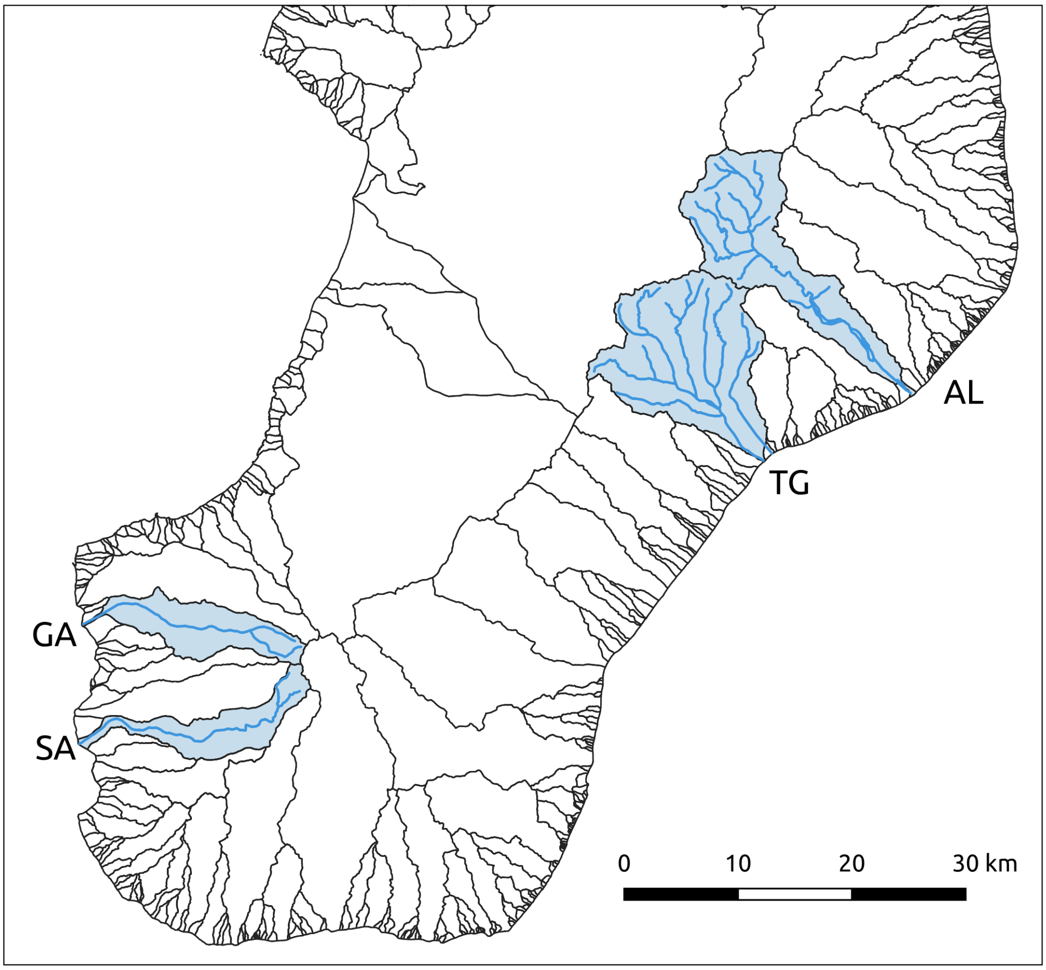
The effects of check dams on the fluvial ecosystem: a brief review on the quantitative methodology developed by Bombino et al. (2006, 2014, 2018, 2019) and Zema et al. (2018)

The studies conducted by Zema *et al.* (2018) and Bombino *et al.* (2019) were carried out in four Calabrian streams, some of which were subject to further analysis, referred to in the next chapter: Allaro "AL", Torbido di Gioiosa "TG", which flow into the Ionian Sea, Sant'Agata "SA" and Gallico "GA", which flow into the Tyrrhenian Sea (Figure 1). All of them are located in the same pluviometric region (Versace *et al.*, 1989) and their small watersheds are fed by contributing areas of similar size and times of concentration. Their characteristics are summarized in the table 1. The analysis are focused on the catchments headwater, were the anthropic actions are low, and the land use, according to the CLC classification of 2016, is predominantly forest (mainly *Fagus sylvatica L.*, *Pinus nigra* *ssp. laricio var. calabrica* and *Abies alba Mill.*) and shrub; intensive crops (on average 20% in the four basins area) and complex crop system (on average about 5%) (Zema *et al.*, 2018).

The soils are mainly Humic Dystrudept in SA and G headwaters (56% and 47% of the area, respectively), Humic Lithic Dystruxerodept in "TG" (44%), and Dystrudepts in A (39%) (USDA Soil Taxonomy classification, 1999). Other soils of the four headwaters are Typic Dystrudepts and Humic Dystruxerodept. Bed surface material has a median particle size typically 84 (A) to 92 (SA) mm (Table 1) (ARSSA, 2003). As lithologic aspects, the upper part of the studied headwaters mainly consist of Micaschist, paragneiss, phyllite and marbles (in TG and A) and granites/granodiorites rocks (in SA and G), which are altered, cracked and easily erodible (Sorriso-Valvo and Sylvester, 1993).



(a)



(b)

Figure 1a, b. Localization of four watersheds selected as study cases: (Allaro - AL, Torbido di Gioiosa - TG, Sant'Agata - SA and Gallico - GA) (Zema *et al.*, 2018; Bombino *et al.*, 2019).

Table 1. Watershed and headwater main characteristics of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Characteristics	**Allaro (A)**	**Torbido di Gioiosa (TG)**	**S. Agata (SA)**	**Gallico (G)**
Watersheds [(a)]				
Area (km^2)	132.2	160.1	61.0	55.5
Mean watershed slope (%)	20	22	29	26
Length of main stream (km)	21	17	24	26
Mean slope of main stream (%)	5.5	7	6.7	7.2
Total number of check-dams	44	196	130	107
Headwaters				
Climate				
Average annual air temperature (°C) [(b)]	10.7±0.6	11.2±0.9	11.1±0.9	9.9±0.8
Average annual rainfall depth (mm) [(c)]	1780±550	1775±50	1351±50	1438±50
Morphology				
Area (km^2)	47	10	22	26
Maximum altitude (m a.s.l)	1395	1215	1580	1730
Minimum altitude (m a.s.l.)	1110	850	910	875
Length of main stream (km)	5.6	3.7	7.0	4.5
Land use				
Main land use[(d)]	Broad lived forest	Broad lived forest (Oakwood)	Mixed forest (Chestnut)	Mixed forest (Chestnut)
Main aspect of vegetation	Woodland			
Main vegetation association	*Alnetum glutinoso cordateae*			*Populetalia albae*
Soil				
Main texture[(e)]	Sandy loam			
Main type[(e)]	Humic Dystrudept			
Main lithology[(f)]	Granites and granodiorites		Micaschist, paragneiss, phyllite and marbles	

Notes: [a] Estimated from 1:25000 scale maps; [b] Estimated from the relationships $T_m = 18.294 - 0.007A$ for the Ionian coast and $T_m = 16.913 - 0.006A$ for the Tyrrhenian coast, both developed using gauged data within the basins (T_m = Mean annual temperature, °C; A = Altitude, m (average ± one standard deviation)); [c] Estimated by using the isohyetal method (average ± one standard deviation); [d] Corine Land Cover (2012); [e] USDA soil taxonomy classification (1975); [f] Geological Map of Italy scale 1:50000 (1976)

Firstly Zema *et al.* (2018) and secondly Bombino *et al.* (2019) carried out analysis on the four torrents following the approach proposed by Bombino *et al.* (2006), schematized below:

- Four check dams, sufficiently old (40 ÷ 50 years) for their impact on the river channel morphology and longitudinal slope (with respect to conditions before check dam construction) as well as riparian vegetation to be fully developed, were selected in each headwater of the four studied torrents;
- five reaches, one for each headwater, containing a check dam, were identified. In every reach three transects were individualized (Bombino *et al.*, 2006) (Figure 2):
    - two transects positioned near check-dams, one upstream (henceforth indicated by the letter U) and one down-stream (D), positioned at a distance from the check dam equal to the height of the check dam itself;
    - the third transect positioned in an intermediate zone between the dams (assumed as control zone and henceforth indicated by the letter C), representative of sites less disturbed by the presence of the check dams because positioned at sufficient distance reasons why the local influence of the check dam on the channel can be considered negligible.

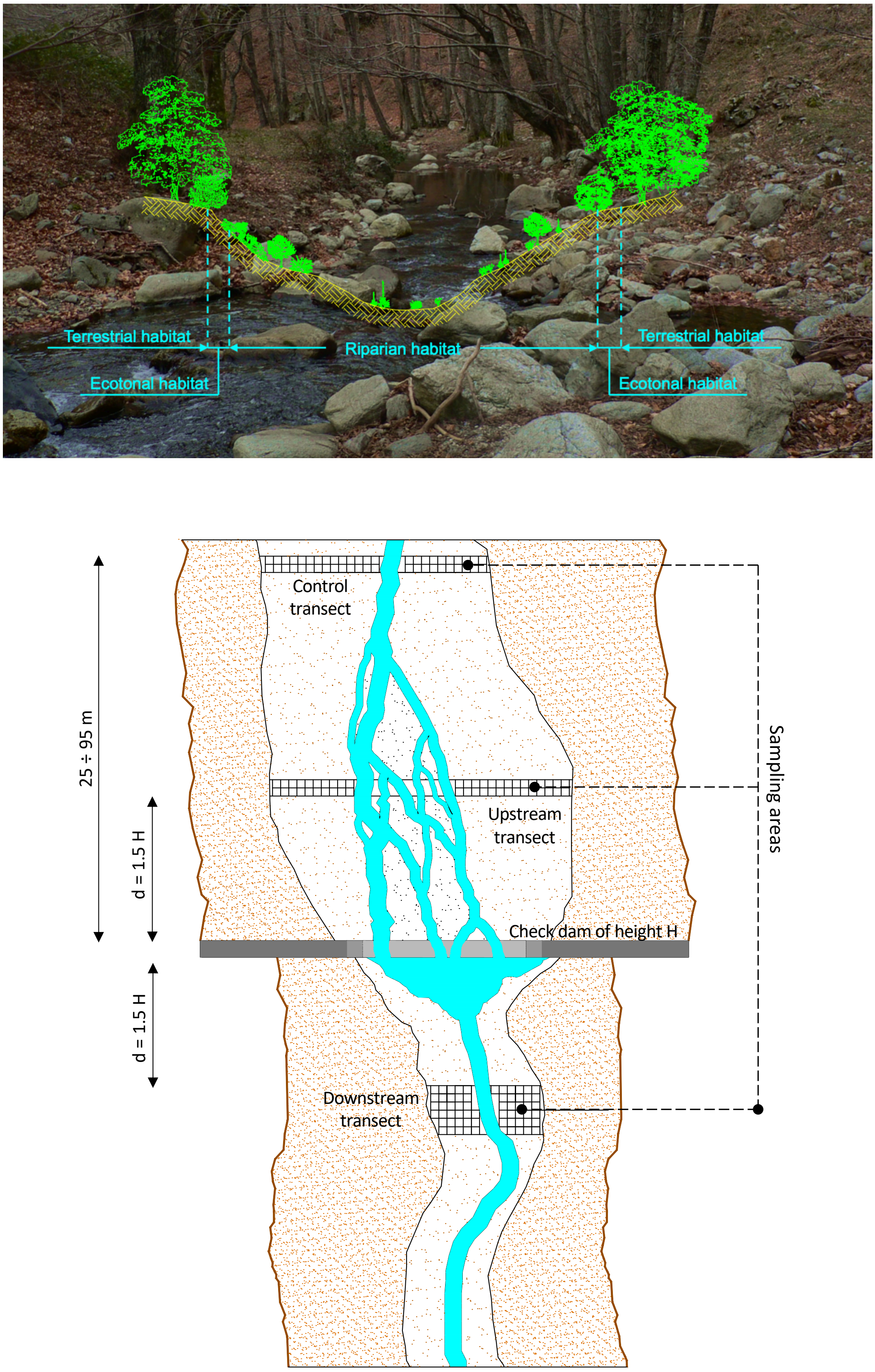


Figure 2a, b. Schematic cross section (a) and layout and subdivision of transects in the mountain reaches (Zema *et al.*, 2018).

In order to investigate physical and vegetation local characteristics of the channel and to carried out a quantitative approach, Zema *et al.* (2018) studied channel morphology, hydraulic regime, nature of bed sediment (surface and sub-surface), riparian vegetation characteristics such as development (extension structure and spatial distribution) and biodiversity (species richness, relative abundance and degree of integrity), selecting many synthetic and representative parameters (Table 2) for:

a) channel morphology: (i) the "width to depth ratio" (w/d, [m m^{-1}]) of the transect section, indicative of its shape, (V-shaped, typical of downstream transects) (U-shaped, typical of upstream transects) (Conesa-García & García-Lorenzo, 2010); (ii) the local slope (LS, [%]) of the longitudinal profile of the thalweg;
b) torrent hydraulic regime: the discharge per unit width (q, henceforth called "specific discharge") required to fill the active channel;
c) bed material: (i) the median particle size of surface sediments (SD50, [mm]); (ii) the percentage of subsurface finer sediment (SSF, [%]);
d) development of riparian vegetation: (i) the Global Canopy Cover (GCC, [%]) (Bombino *et al.*, 2016), which represents the sum of the percent cover of the herbaceous, shrub and tree layers multiplied, respectively, by 1/6, 2/6 and 3/6 to take into account the ecological importance of each layer, with values falling in the range 0% to 100%; (ii) the Weighted Canopy Height (WCH, [m]), that is the sum of the products of the average height of the individual layers (herbaceous, shrub, tree) and the corresponding canopy cover; (iii) the Coefficients of Variation of the two parameters above mentioned (CV_{GCC}, [%], CV_{WCH}, [%]) to describe the spatial distribution of the riparian vegetation (the transverse variability of extension and structure);
e) biodiversity of riparian vegetation: (i) the α-diversity index (H_α), proposed by Hill (1973), which measures the species richness for $\alpha = 0$, and the relative abundance for $\alpha = 2$.; (ii) the ratio (Ns_A/Ns_N) between the number of alien (A) and native (N) species in each transect, which measures the degree of integrity of vegetation.

In the Figure 3, a scheme of the channel and vegetation characteristics of Mediterranean semi-arid headwaters under natural conditions and after check dam installation.

Table 2. Physical and vegetation indicators adopted in this study together with their significance and survey/calculation methods (Zema *et al.*, 2018).

Effect		**Indicator**	**Significance**	**Range of variability**	**Survey**	**Calculation method**
PHYSICAL	*Morphology*	w/d	Cross section shape	$0 \div \infty$	Field topographic survey	ratio between channel width and maximum depth
		LS	Longitudinal slope			
	Hydraulic	q	Flow regime			Manning's equation
	Sediment	SD_{50}	Surface sediment size		Sediment grain size measurement	Adams (1979)
		SSF	Finer sub-surface sediment content	$0 \div 100\%$	Laboratory sieving	-
VEGETATION	*Development*	GCC	Extension		Field survey	Bombino *et al.* (2006, 2014)
		WCH	Structure	$0 \div \infty$		
		CV_{GCC}	Transversal variability of extension			
		CV_{WCH}	Transversal variability of structure			
	Biodiversity	H_0	Species richness		Field survey	Hill (1973)
		H_2	Relative abundance			
		Ns_A/Ns_N	Degree of integrity		Field survey	-

The statistical significance of indicators calculated in U, D and C transects were investigated by Kruskal-Wallis tests (a non-parametric alternative to analysis of variance) followed by multiple pairwise comparisons using Dunn's procedure with Bonferroni's correction for the significance level for the pairwise comparisons (Zema *et al.*, 2018). Later, in order to identify possible mathematical relationships between couples of physical and vegetation indicators, Pearson's correlation matrix was computed based on their current values regardless the transect group (that is, without considering whether an indicator relates to U, D or a C transect. Preliminarily, the indicators were standardised, then Agglomerative Hierarchical Cluster (AHC) analysis was applied to the indicators, in order to find groups of transects with similar characteristics. AHC is a distribution-free ordination technique used to group features (in our case the transects) in clusters with as much similar characteristics (in this case the indicators). All statistical analyses were performed using XLSTAT® release 2017 (Zema *et al.*, 2018).

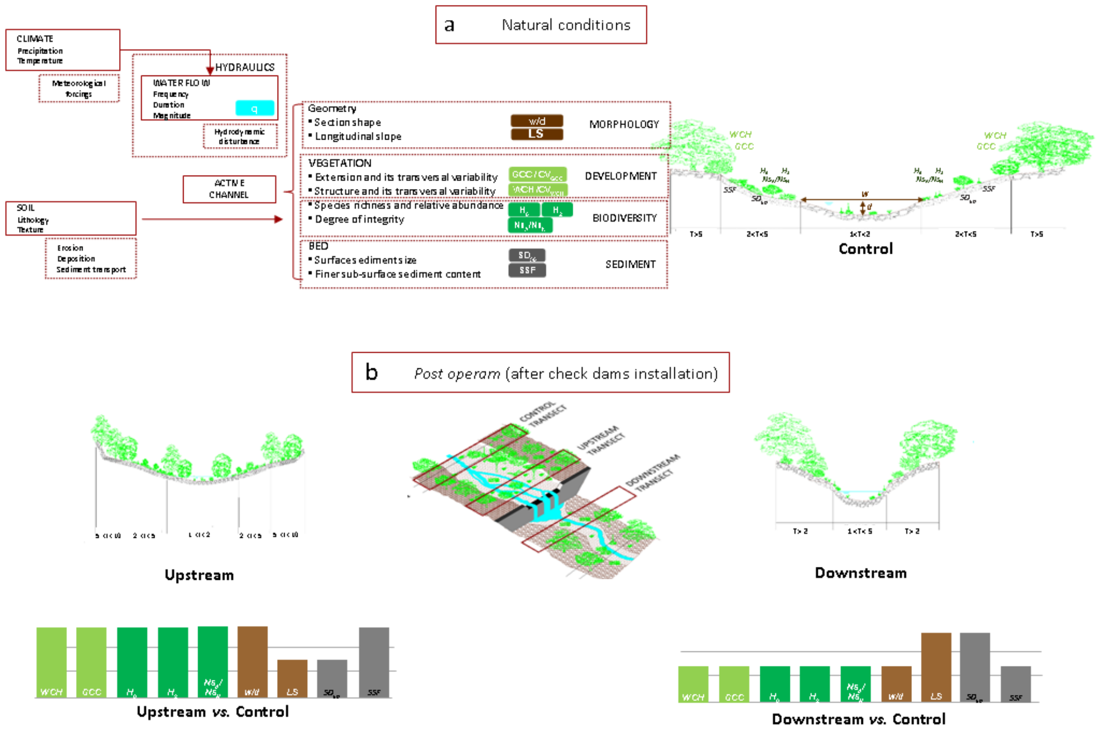


Figure 3. A scheme of the channel and vegetation characteristics of Mediterranean semi-arid headwaters under natural conditions and after check dam installation.

Later, Bombino *et al.* (2019) applies multivariate statistical techniques (Principal Component Analysis and Partial Least Square Regression) to identify in the same study headwaters new synthetic explanatory variables, representative of the different transects (U, D and C) and develop predictive models of riparian vegetation characteristics. In this case, to evaluate the statistical significance of differences among the physical and vegetation parameters sampled at each transects, a two-way analysis of variance ("ANOVA") was applied. Subsequently, since the relationships between physical and vegetation indicators are complex and are influenced by several factors of different nature (morphological, sedimentary, hydrological, and biological) and modified by the presence of the check dams, the Principal Component Analysis ("PCA") was used to reduce the dimensionality of the data set of the indicators (correlated each other), discriminating the physical and vegetal characteristics of torrents according to the transect group (upstream, downstream or intermediate) and loosing as little as possible information. So, a lower number of derivative and uncorrelated variables, called "principal components" (PCs) was identified, able to simplify the analysis of the highly complex processes standing behind check dam actions. Finally, multiple regression models were built - separately for each transect group (U, D and I) - between the physical indicators on one hand

(independent variables "x") and vegetation indicators on the other hand (dependent variables "y"). The models were provided by the non-parametric Partial Least Square Regression ("PLSR") technique, a method for constructing predictive models when the factors are many and highly collinear. This technique was developed by Wold for econometrics (Wold, 1975) and then extended to other scientific fields; it is an extension of multiple regression analysis, in which the effects of linear combinations of several predictors (in our case the morphological, hydraulic and sediment indicators) on multiple response variables (here, the indicators related to the riparian vegetation) are analysed (Bombino *et al.*, 2019).
The studies carried out by Zema *et al.* (2014, 2018) confirmed how much the control works significantly change cross section shape, hydraulic regime and bed sediment characteristics of headwaters. In particular, check dams were found to influence significantly unit discharge, surface and subsurface sediments (both upstream and downstream), channel shape and transverse distribution of riparian vegetation (upstream) as well as cover and structure of riparian complexes (downstream), while the actions of the control structures on torrent longitudinal slope and biodiversity of vegetation were less significant. The results of the Agglomerative Hierarchical Cluster analysis confirmed the substantial similarity between upstream and control transects, thus highlighting that the construction of check dams, needed to mitigate the hydro-geological risks, has not strongly influenced the torrent functioning and ecology as it was before check dam installation.

From regressions between cover, structure, transverse variability of riparian vegetation and morphological, hydraulic and sedimentary variations of channel characteristics induced by check dams, done by Zema *et al.* (2018), it results that simple and quantitative linkages between torrent hydraulics, geomorphology and vegetation characteristics exist in the analysed headwaters. In fact, high coefficients of correlations were found for the majority of the linear regressions. these relationships among physical adjustments of channels and most of the resulting characteristics of the riparian vegetation are specific for the transect locations with respect of check dams. Conversely the biodiversity of the riparian vegetation basically eludes any quantitative relations with the physical and other vegetal characteristics of the torrent transects.

Overall, the quantitative approach of this analysis helps a better comprehension of physical processes and vegetation response in very constrained headwater locations of the Mediterranean torrents.

Moreover, analysis carried out by Bombino *et al.* (2019) highlighted that the geographic position of the studied watersheds determined statistically significant differences only for few physical (that is, those related to surface and subsurface sediment grain size) and biodiversity (that is, evenness and degree of integrity) indicators. The PLSR models proposed may be very helpful: (i) to plan and design new check dams, since their the structure effects on the development and growth of vegetation upstream and downstream can be forecasted before their installation (at least for the quantification of the order of magnitude of the check dam impacts on torrent ecology); (ii) to delineate ecological scenarios after installing the river control works, which avoids ad hoc experimental tests at a real scale, needed to evaluate the effects that such works exert on the evolutionary tendency of the water course and riparian vegetation; (iii) to lower difficulties and uncertainties in the authorities' approval process for torrent control works; (iv) to comply with the requirements of the Water Framework Directive promoting integrated catchment management to achieve an optimum ecological state in river systems, with particular reference to the vegetation. Overall, the relevant methodology applied in the study of Bombino *et al.* (2019) has proved to be sensitive and effective in isolating differences between transects and associations between physical and ecological variables around check dams.

PREMISE

The methodologies developed and their application herein described, have allowed a quantitative evaluation of the effects locally induced by check dams in the mountain reaches and in particular on channel morphology, hydraulic regime, nature of bed sediment and riparian vegetation. The in-depth study of this starting point has highlighted the possibility of exploring a broad scenario of research, especially with reference to the need to characterize the flash floods that can affect the riparian ecosystem evolution. The current arrangement of the ecosystem, in fact, represents a "snapshot" of the riparian vegetation characteristics (in terms of organization, structure and biodiversity) near the check dams, observed at the time of the survey (Figure 4a). The ecosystem is affected not only by the interaction with the artifact, but also by the hydrological processes that take place in the headwaters. Especially, as is known, the flash floods with longer recurrence intervals can lead to drastic changes in the river environment and, often, cause the reset of plant formations, keeping the ecosystem in a perennial condition of *non-equilibrium*.

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 & Tropeano, 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; Lucía *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 billions 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 & Baker 1982; Baker, 1983; Benito *et al.*, 2003, Baker, 2008; 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; Hooke 2007; Osterkamp & Hupp, 2010). 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 & Jarret, 2002) of past flood activities and are sometimes also defined as "paleostage indicators" (PSI; Baker *et al.*, 2002; Jarrett & England, 2002; Ballesteros *et al.*, 2015a) (Figure 4b). PSI are fundamental for flood reconstruction as they offer reliable estimates of past flood frequency (Harrison & Reid, 1967; Gottesfeld & Gottesfeld, 1990; Zielonka *et al.*, 2008; Ruiz-Villanueva *et al.*, 2010) and/or magnitude (Sigafoos, 1964; Yanosky & 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 (Ballesteros-Canovas *et al.*, 2015b; Fortugno *et al.*, 2017); scars in trees have therefore been used in different environments across the globe to reconstruct past floods, especially in Central and Northern Europe and in North America (Sigafoos & Hendricks, 1961; Sigafoos, 1964; Helley & LaMarche, 1973; Yanosky, 1982; Hupp, 1988; Jarrett & 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.

AIM

In order to compensate for the lack of hydrological data, the aim of this PhD Thesis work is to reconstruct 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* (typical streams of the semiarid Mediterranean environment of southern Italy.)

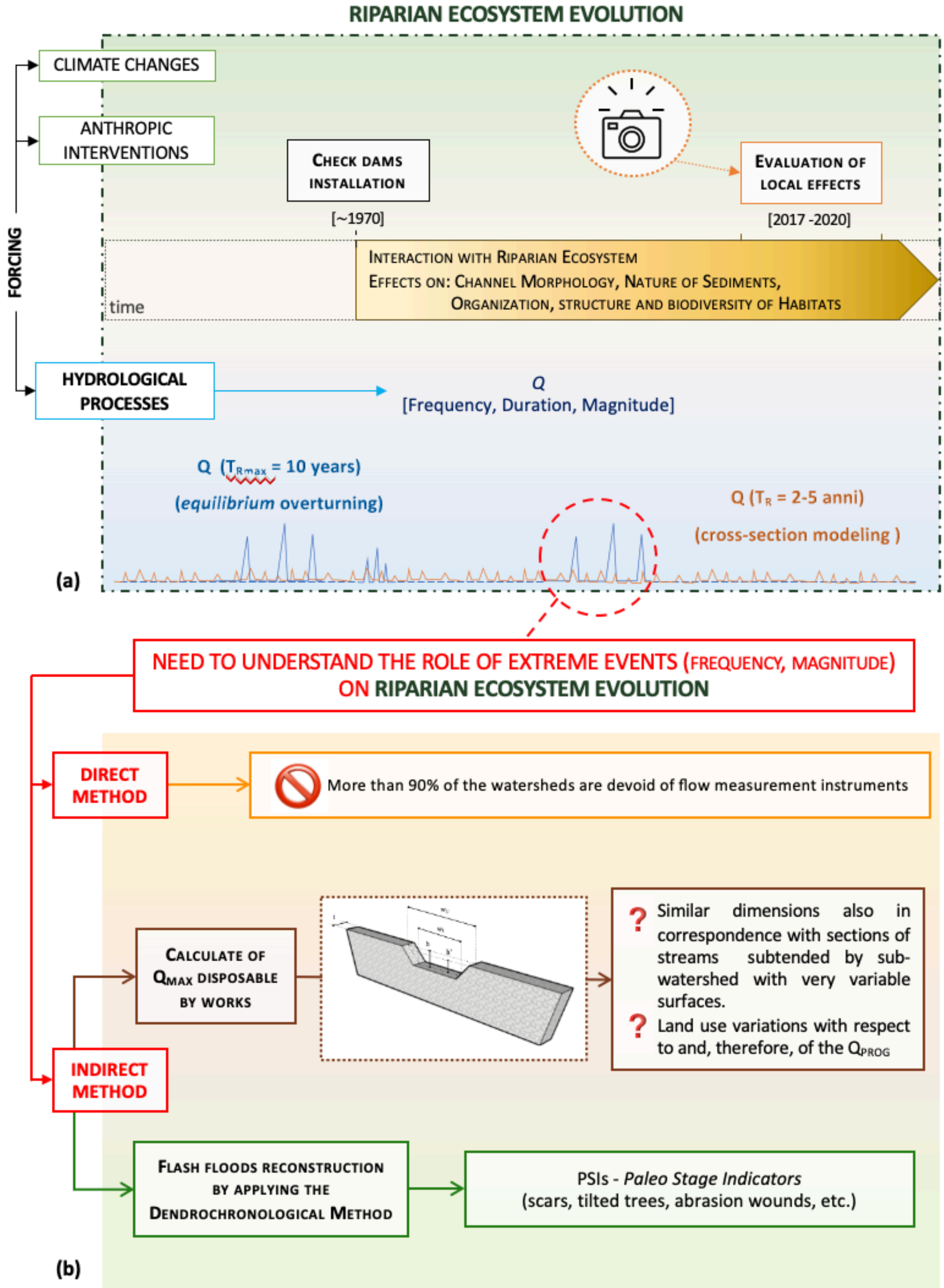


Figure 4. *Graphical abstract*: the evolution of riparian ecosystems in mountain streams of the Mediterranean environment is mainly affected by the presence of engineering control works and flash floods due to intense rainfalls. Tree-ring based reconstructions of past flash floods were carried out, in order to characterize flash flood in space and time, in small mountain catchments of the Mediterranean basin.

MATERIALS AND METHODS

STUDY AREA

The study was carried out in Calabria, the southern region of Italy. According to the Mediterranean climate, there are mild winters, and hot summers, with intense rainfall events during autumn and winter, while few rain events occurring in spring and summer seasons (Bombino *et al.*, 2006). The Ionian side is affected by air masses coming from Africa and shows higher temperatures with short and heavy rains; the Tyrrhenian side is influenced by western air masses and has milder temperatures and frequent rain. According the Köppen-Geiger classification (Kottek *et al.*, 2006), the climate can be classified as Csa (mild temperate, dry and hot summer, in coastal zones) and Csb (mild temperate, dry and warm summer, in internal areas).

The average regional annual rainfall is between 1351 and 1780 mm. Therefore, there is a particular pluviometric and hydrological regime with short, intense and discontinuous rains that affects a territory with a complex orography. In fact, the region is very rugged: only 10% of territory is plain, while the remaining area shows hilly and mountainous structure. The geographical shape of Calabria is long and narrow, with a minimum width of 31 km and maximum of 111 km; the difference between the coast and the highest hills is approximately equal to 2000 m a.s.l. and therefore in a strong slope within a few kilometres.

The regional morphology is dominated by tectonics, with mountains and plain areas corresponding to uplifted blocks and intervening downlifted blocks, respectively. Because of the combination between geodynamic, lithology and geomorphology, the region is covered for about 90% by hilly and mountainous areas, with a very small extent of the flat areas. All of these characteristics prevented the formation of evolved river systems.

Typical watercourses of the region, also named *fiumaras* (Bombino *et al.*, 2009; Ballesteros-Canovas *et al.*, 2020), are torrents or ephemeral streams, characterized by typical torrential hydrological regime, small catchments with a concentration time of pick discharge of few hours), huge sediment and high and impulsive floods ("flash floods") able to activate high water and sediment flows (Fairbridge, 1968; Jarrett, 1990; Borga *et al.*, 2007; Gaume *et al.*, 2009; Ruiz-Villanueva *et al.*, 2010), very steep slopes and riverbeds in the headwaters and usually flat, braided and wide riverbed, covered with coarse-grained alluvium, near the coast (Sabato & Tropeano, 2004).

Generally, the flow regime is intermittent in the lower-order streams and perennial in the main reach, and is affected by sudden storms and, once every almost two or three years, by episodic and intense flash floods, 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; Lucía *et al.*, 2015).

The combination between natural characteristics (aggressive climate and hydro-geomorphology) and anthropic actions (human activities and pressure, unsustainable soil management and land use change occurred over the years), have made that floods events become disruptive (Wohl, 2017; Rodrigues *et al.*, 2018). In mountain streams, characterized by high longitudinal gradients and concentration times of less than 2 h, 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). In these streams, the lower discharges (recurrence time of 1.5 to 2 years) can be responsible for cross-section modelling and resulting landforms (Leopold *et al.*, 1964; Gregory & Walling, 1973; Richards, 1982) with no heavy geomorphic adjustments on bed longitudinal profile (Fortugno *et al.*, 2017); flash floods with longer recurrence intervals (5–10 years or more) (extreme events) have the major effects on channel morphology and ecology: they can remodel the torrent morphology by erosion and transport processes active along hillslope and delivered channel, overturning and often resetting the fragile *equilibrium* of the fluvial ecosystem.

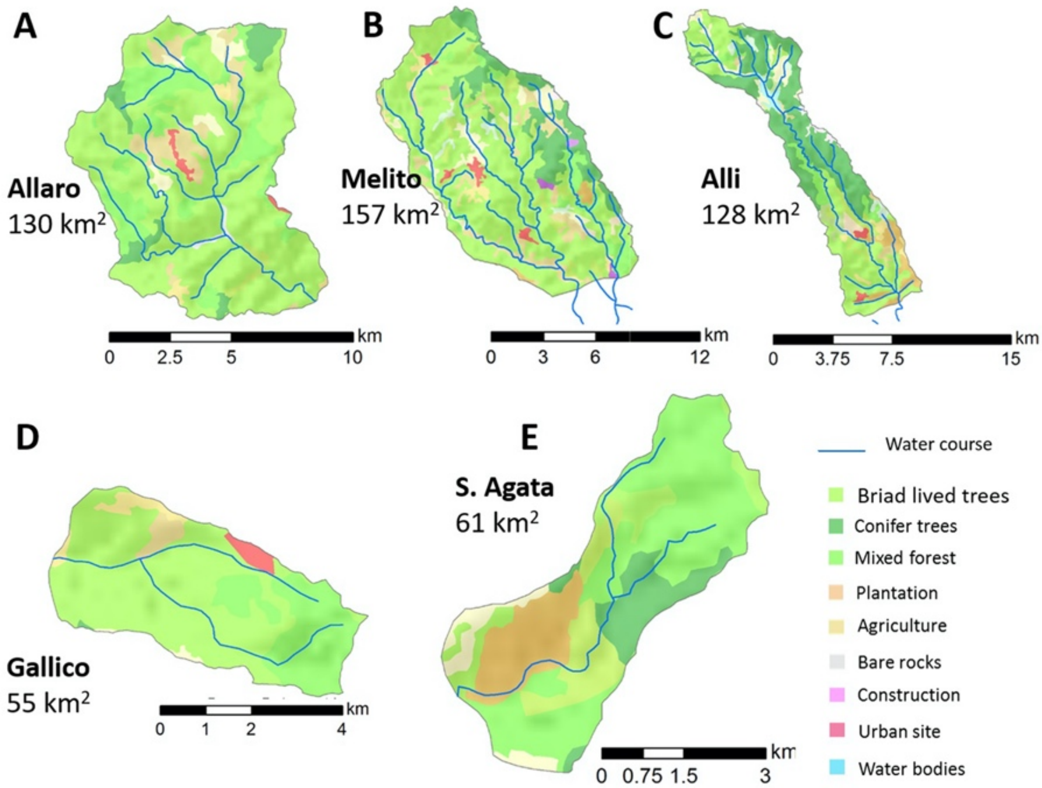
For this study, five mountain torrents in Calabria were selected: two of these are ungauged (Gallico, hereafter "GA"; Sant'Agata, "SA"), whereas three have a significant observational record (Allaro, "AL"; Alli, "AI"; Melito "ME"), (Figure 5; Table 3). The selection of the 5 catchments was guided by 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. The headwaters of these *fiumaras*, representative of mountainous watercourses of Calabria and Sicily, exhibit perennial flow and steep longitudinal profiles (Photos 1). 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.

Table 3. 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°03 N	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. (ARPACAL web site: https://www.cfd.calabria.it/index.php/dati-stazioni/dati-storici)

(a)



(b)

Figure 5a, b. Location and map of the five studied catchments with the relative land use.

Photos 1. Characteristic views of the mountain reach of the Gallico (a), Sant'Agata (b), Allaro (c), Melito (d) and Alli (e) catchments.

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 3); their morphology can be classified as 'alluvial cascade' according to Montgomery & 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 (Kottek *et al.*, 2006)), 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).

The lithology consists of Palaeozoic metamorphic rocks (mostly micaschists, amphibolites, phyllites, quartzites and granitic gneisses) and Pleistocene sedimentary 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* (Kottek *et al.*, 2006), *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 & Mercuri, 1980).

METHODOLOGY

Dating of past floods and estimation of their peak discharge was undertaken through the integration of dendro-geomorphic, hydrological and hydraulic analyses (Yanosky & Jarrett, 2002; Ballesteros Canovas *et al.*, 2011a; 2011b). To this end, the following working steps have been undertaken (Figure 7): (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.

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 included scars, tilted trees, equally aged trees, sprouts from tilted parent trees (Photos 2) 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 (Zielonka *et al.*, 2008; Ballesteros *et al.*, 2011a, b). 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 & 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 & 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; Figure 7).


(a)


(b)

(c)

(d)

(e)


(f)


(g)

(h)

Photos 2. (a) tilted tree due to a flood flow (GA catchment); (b) transversal section of tree trunk with corrasion scar and evident signs of eccentricity; (c) tree (*Salix alba*) uprooted by a flood flow (SA catchment); (d) sprouts from felled parent trees of advanced age of Black Alder (*Alnus glutinosa*) (GA catchment); (e) group of equal in age Alders grown along the banks (GA catchment); (f) corrasion scar on Alders located in the GA mountain reach; (g) stone materials retained by Alders roots; (h) torrent reach characterized by rocky banks and armored riverbed bottom.

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.

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 time-windows, namely 1951-1965, 1966-1980, 1981-1995, and 1996-2010.

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 & Baker, 1988; Benito & O'Connor, 2013) (Figure 6; Photos 3). For each cross-section (Figure 7), 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.

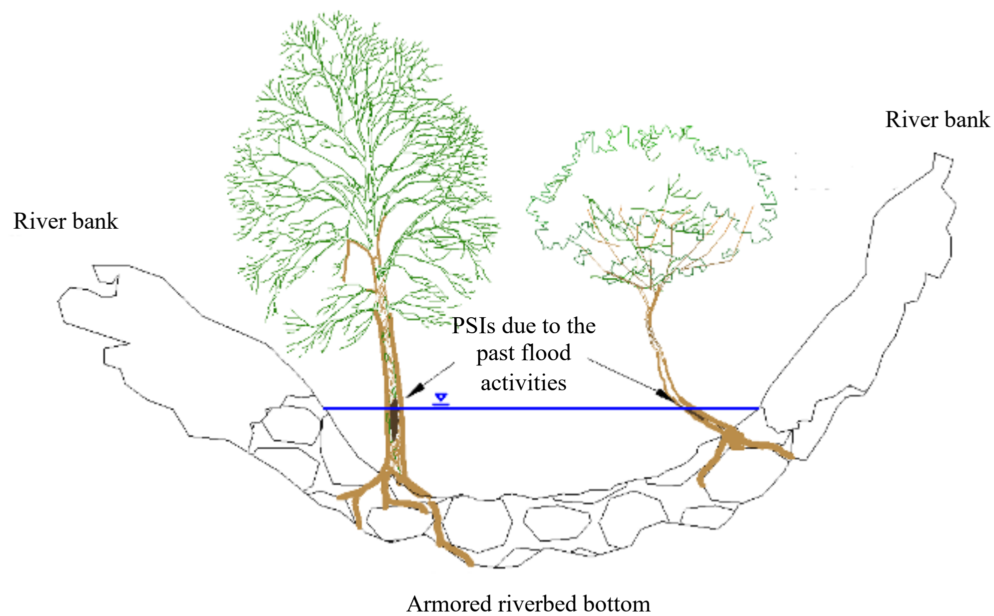


Figure 6. Schematic stable cross section and reconstruction of a hypothetical water depth corresponding to a flood responsible of a PSI.

(a)

(b)

Photos 3. Stable cross section (upstream view) on the mountain reach of Gallico *fiumara* (a) and stable cross section (downstream view) on the mountain reach of Sant'Agata *fiumara* (b).

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 (Figure 7).
In a first step, we applied the "step-backwater" hydraulic approach (O'Connor & 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 (Hazen, 1914; Weibull, 1951; 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.

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 (Figure 8). 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.

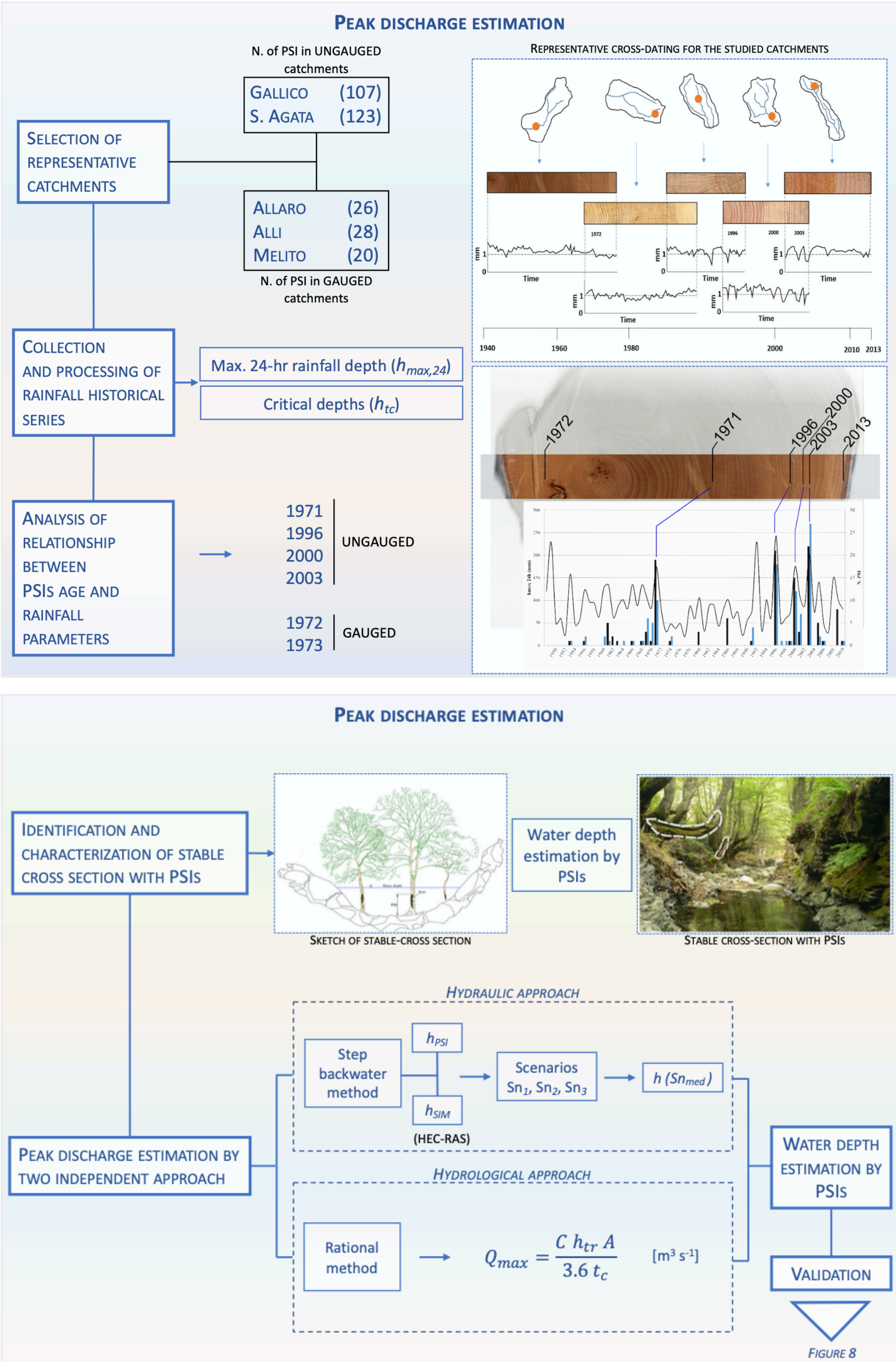


Figure 7. Methodological flowchart used for reconstructing of peak discharge during past flood events based on paleostage indicators (PSIs) and damage in trees in stable cross-sections (h_{PSI} = scar heights; h_{SIM} = HEC-RAS simulated water depth; Sn_x = scenarios 1, 2, and 3; Q_{max} = maximum discharge calculated with the rational formula).

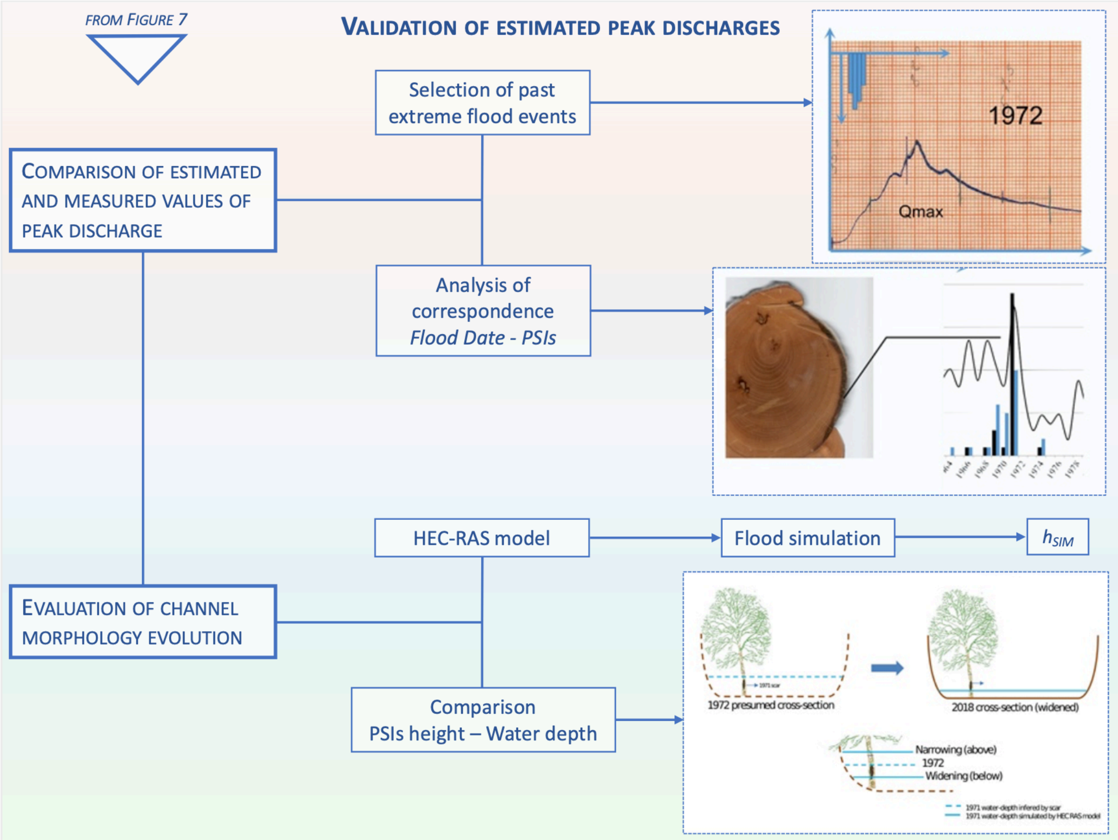


Figure 8. Methodological flowchart used for the validation of dendro-geomorphic method (h_{SIM} = HEC-RAS simulated water depth.

RESULTS AND DISCUSSION

Calculate of Q_{max} disposable by check dams

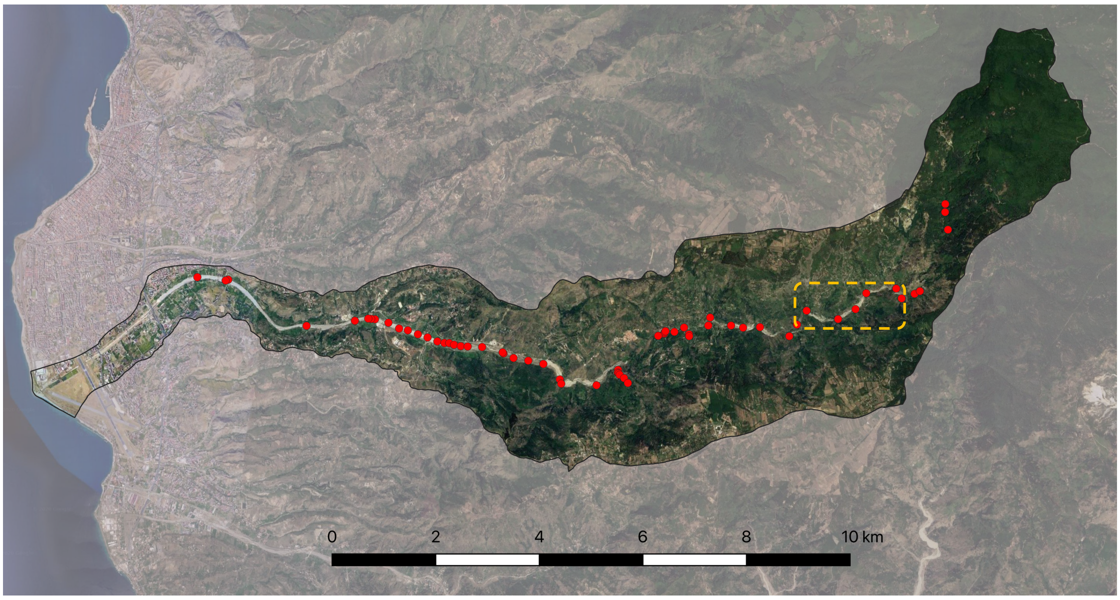
Before integrating the dendrochronological method in the selected case studies, another indirect method was applied, in order to estimate the check dam discharge capacity.
In general, the dimensioning of the spillways is based on relationships like h = f(Q_D): the height of the spillway is sized according to the design flood Q_D. Taking this into account, the fundamental relationships to evaluate h derive from the equations of the flow rate on a thick-walled weir of the type (1) (Ferro V., 2002):

$$h = 0.7\left(\frac{Q}{L}\right)^{2/3} \tag{1}$$

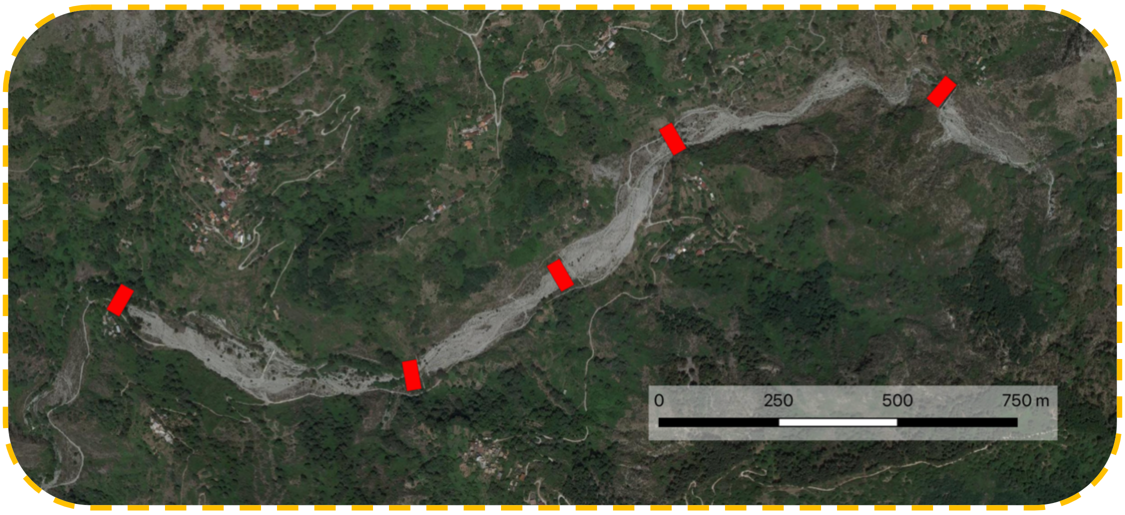
where h and L are respectively the height and the width of spillway, and Q is the design flood.

The value of the maximum discharge capacity of check dams spillway is approximately equal to the value of the design flood used to dimensioning the check dams.

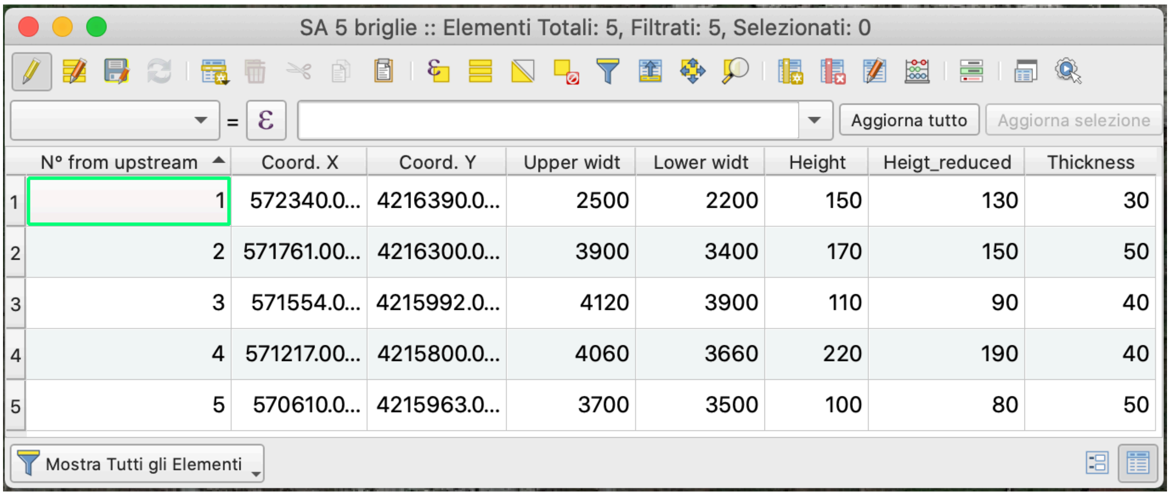
In order to calculate the value of maximum discharge, five check dams were selected in the headwaters of the *fiumara* Sant'Agata: geometric characteristics data have been detected by field surveys and elaborated by using the GIS software (Figure 9; 10).



(a)



(b)



SA 5 briglie :: Elementi Totali: 5, Filtrati: 5, Selezionati: 0

	N° from upstream	Coord. X	Coord. Y	Upper widt	Lower widt	Height	Heigt_reduced	Thickness
1	1	572340.0...	4216390.0...	2500	2200	150	130	30
2	2	571761.00...	4216300.0...	3900	3400	170	150	50
3	3	571554.0...	4215992.0...	4120	3900	110	90	40
4	4	571217.00...	4215800.0...	4060	3660	220	190	40
5	5	570610.0...	4215963.0...	3700	3500	100	80	50

(c)

Figure 9a, b, c. Localization of the five check dams selected in the headwater of the *fiumara* S. Agata (a, b) and characteristics of each spillway (c).

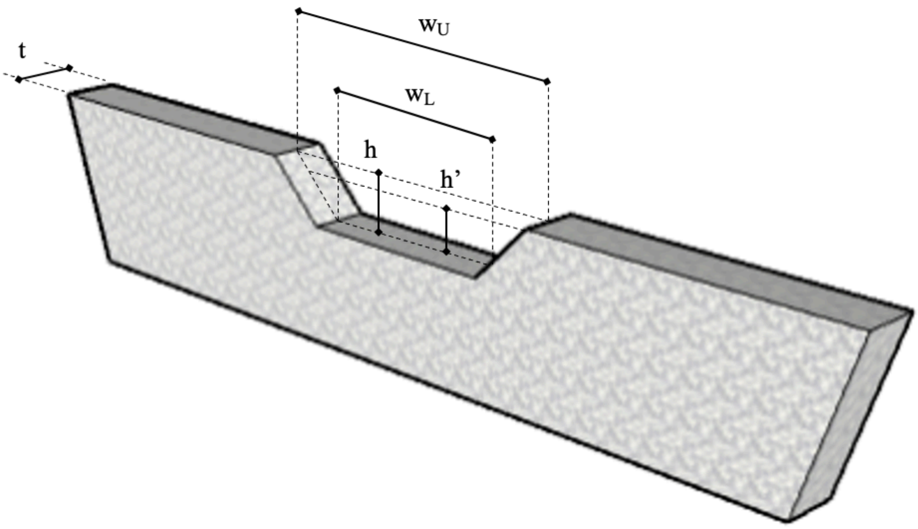


Figure 10. Geometric scheme of a check dams, where w_U and w_L are respectively the upper width and the lower width of spillway, t is the thickness, h is the height and h' height reduced by a value of 20 cm, namely "safety height".

Because the selected spillways are trapezoidal, as in almost all check dams in regional territory, an equivalent width was considered (Benini's Formula, Ferro V., 2002) equal to $L = L^* = w_L + \frac{2}{3}h$; the equation (1) became:

$$h = 0.7\left(\frac{Q}{w_L + \frac{2}{3}h}\right)^{2/3}$$

and therefore:

$$Q' = \left(\frac{h'}{0.7}\right)^{\frac{3}{2}} \cdot (w_L + \frac{2}{3}h') \tag{2}$$

where *Q'* is the value of the maximum value of discharge capable to flow through check dam, and *h'* is the height of the spillway less of safety height, generally equal to 20 centimetres (Ferro V., 2002).

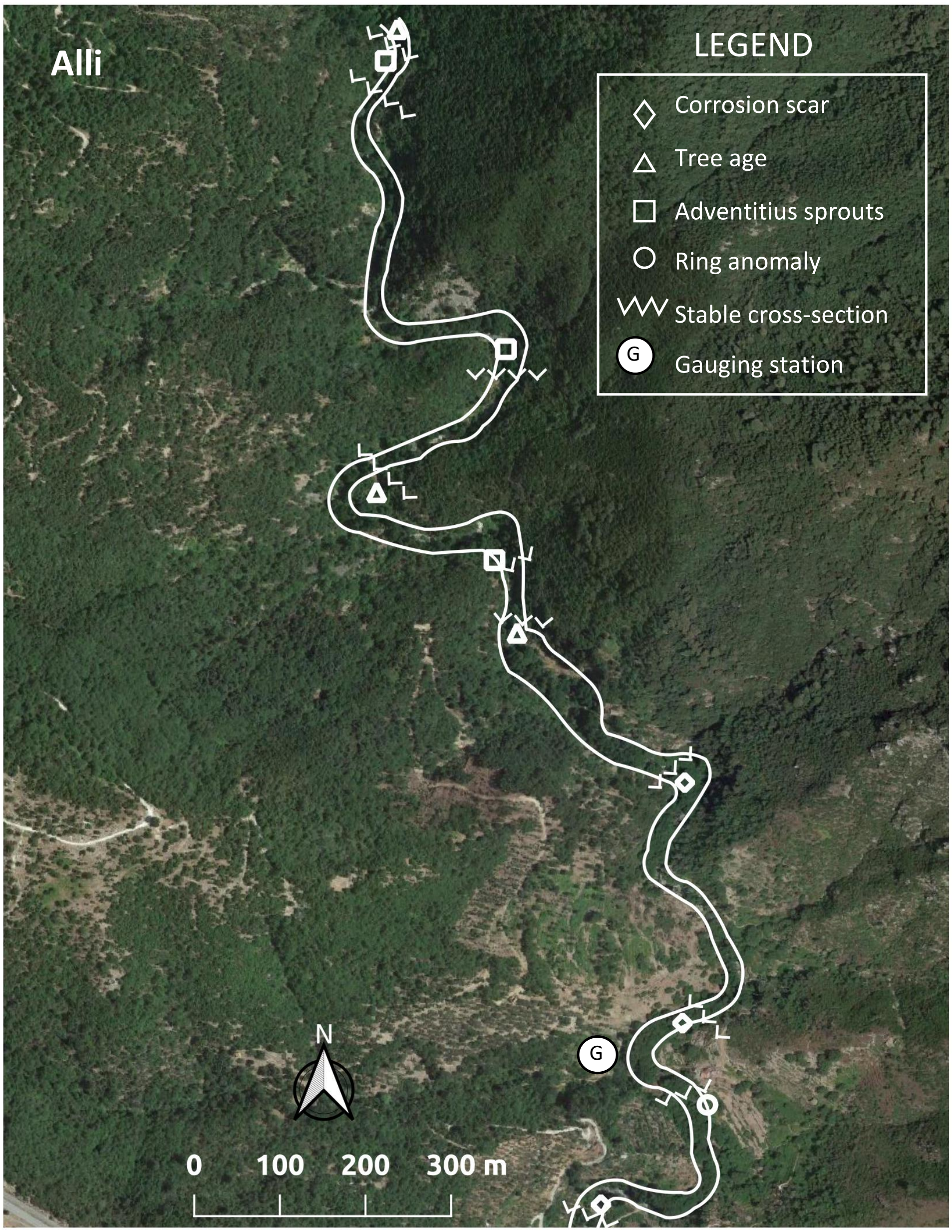
The values of *Q'* calculated for each spillway, by means a simple Excel spreadsheet, are summarized in the following table:

Table 4. Values of characteristic used to calculate the emptiable discharge and Q' values calculated.

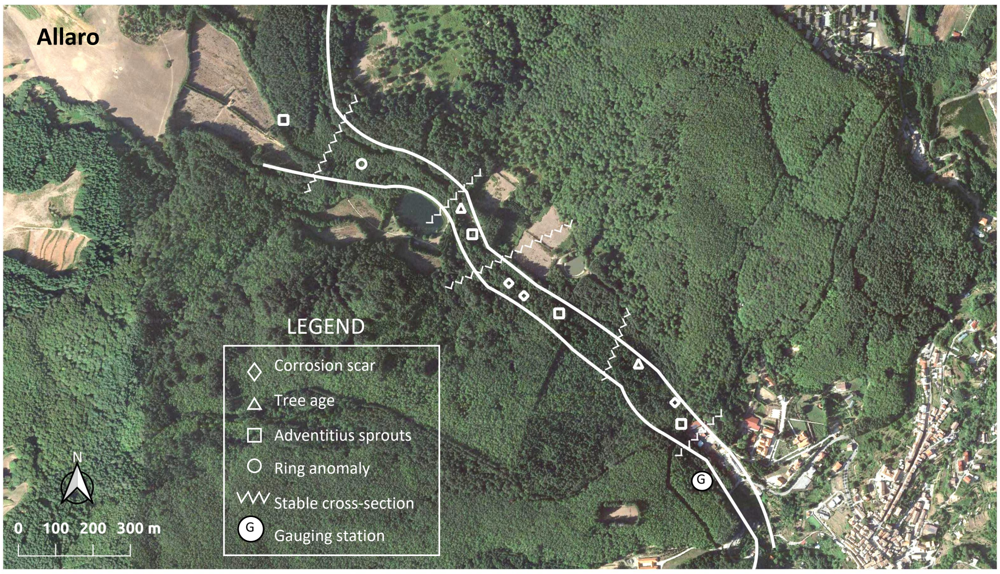
N° check dams from upstream	**t**	**w_U**	**w_L**	**h**	**h'**	**Q'**
	(cm)	(m)	(m)	(m)	(m)	(m^3 s^{-1})
1	30	25	22	1.5	1.3	57.87
2	50	38	34	1.7	1.5	109.79
3	40	41.2	39	1.1	0.9	57.73
4	40	40.6	36.6	2.2	2.0	183.20
5	50	37	35	1.0	0.8	43.41

The wide range of variability of the values of the discharges that can be disposed of from the spillways, despite the selected check dams being very close to each other, would suggest that this method of "reconstruction of the capacity" is not reliable. In fact, in addition to the high variability of Q' values, it is not possible to characterize its frequency and magnitude of discharges.

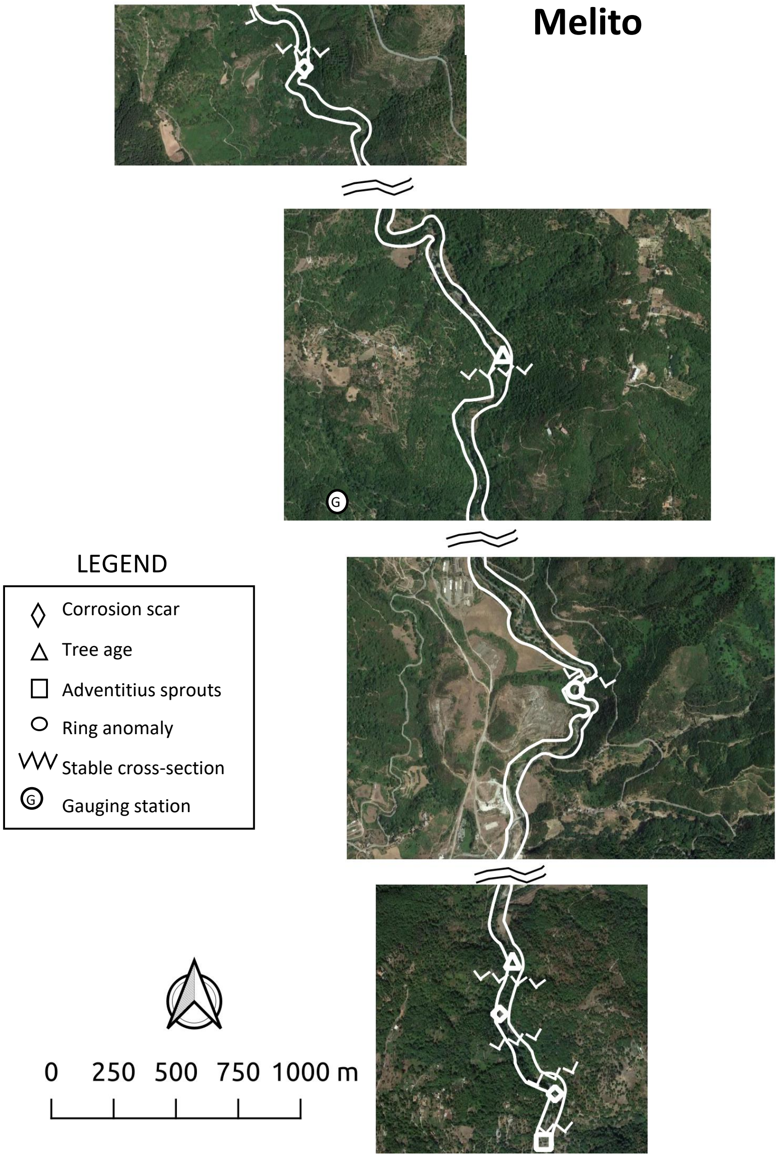
In the sub-reaches of the GA, SA, AL, AI and ME mountain catchments, a total of 55 stable cross-sections were identified with ample evidence of past floods recorded in trees (Figure 11). Within these sections, 107 (GA), 123 (SA), 10 (AL and AI, respectively) and 8 (ME) trees showed PSIs that could be 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 12.



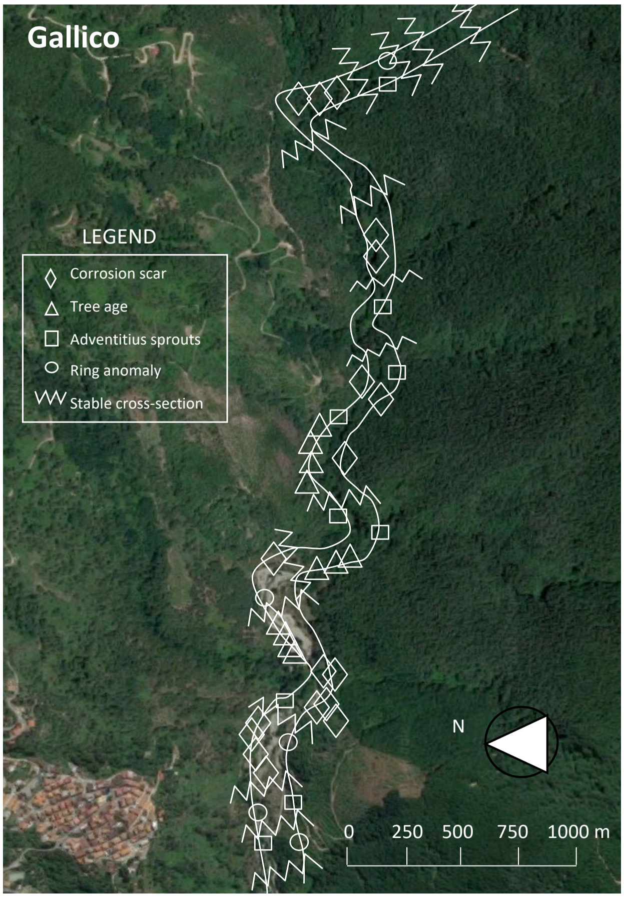
(a)


Allaro
LEGEND
Corrosion scar
Tree age
Adventitius sprouts
Ring anomaly
Stable cross-section
Gauging station
N
0 100 200 300 m

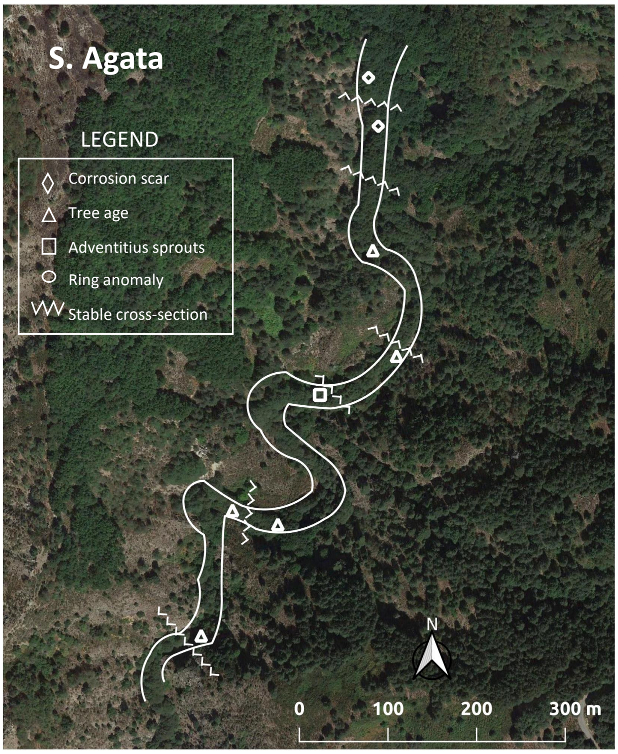
(b)


Melito
LEGEND
Corrosion scar
Tree age
Adventitius sprouts
Ring anomaly
Stable cross-section
Gauging station
0 250 500 750 1000 m

(c)



(d)



(e)

Figure 11. PSIs position in the studied torrents: Allaro (a), Alli (b) and Melito (c) (gauged); (d) Gallico and (e) Sant'Agata (ungauged).

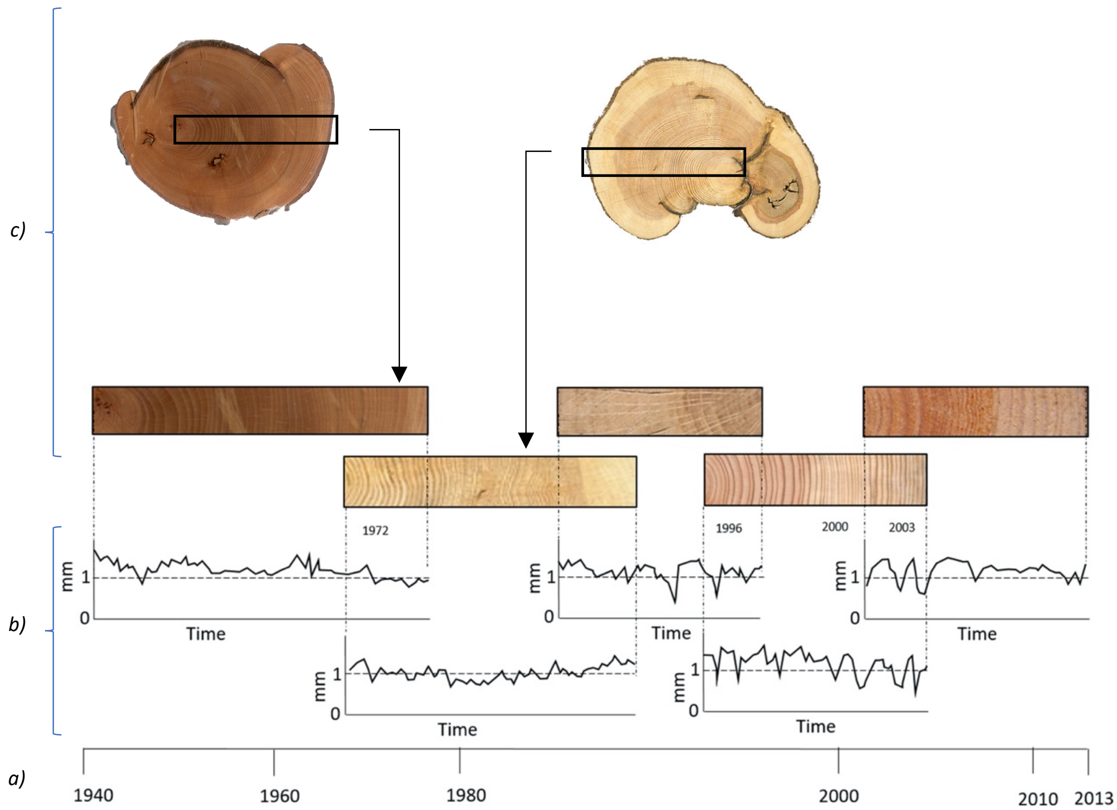


Figure 12. An example of sequence carried out by cross-dating technique, applied in the five studied catchments: a) time-window; b) succession of rings width over time; c) wooden samples.

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 (Figure 13).

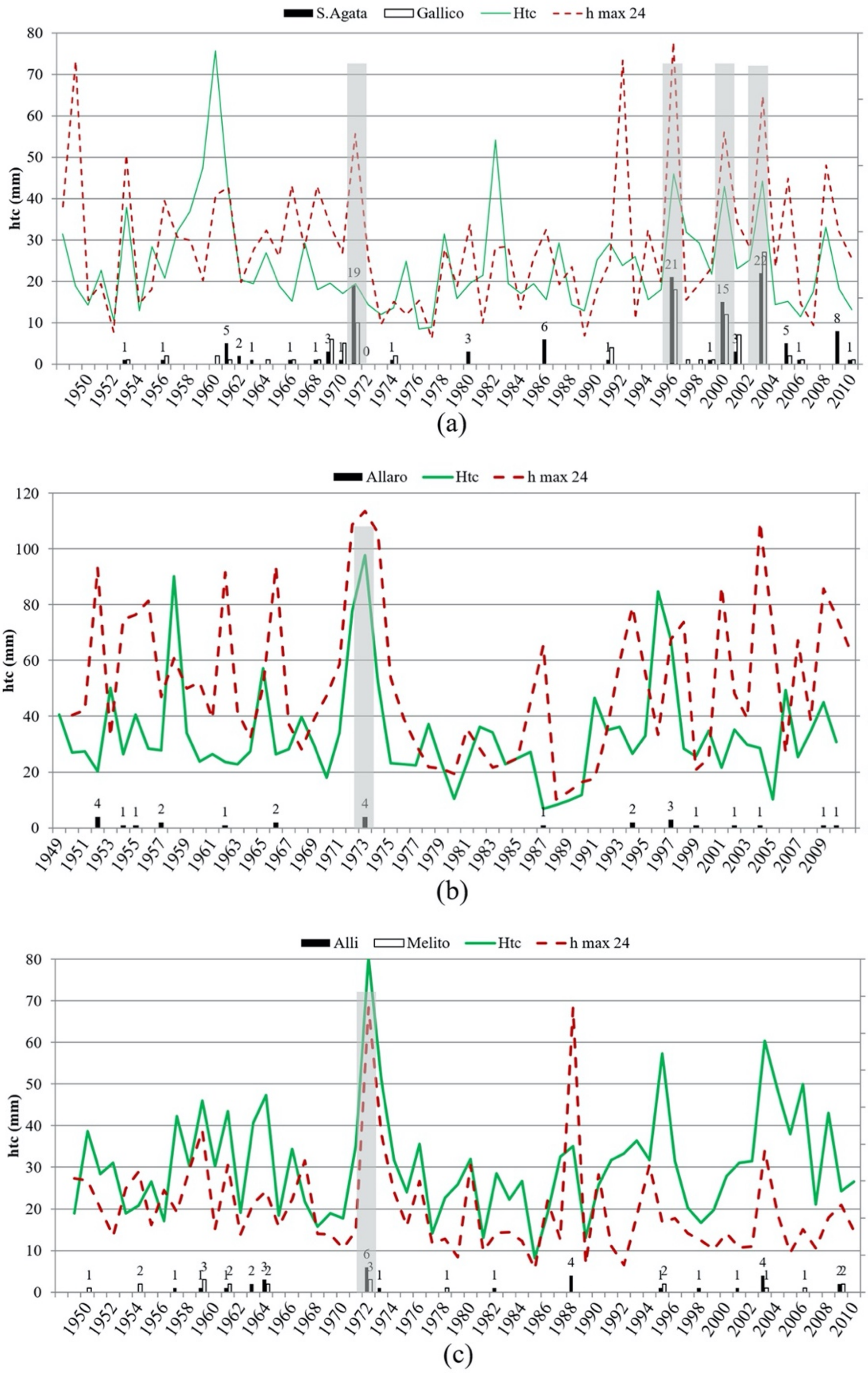


Figure 13a, b, c. Rainfall depth (dashed and full lines are for $h_{max,24}$ = 24-hour maximum rainfall depth and h_{tc} = critical rainfall depth value, respectively) and number of PSIs (at the top of white and black bars) left by floods in reaches of the (a) Gallico, (b) Allaro and (c) Alli / Melito 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 (Figure 14 - for simplicity, Figure 14, 15 and 16 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) (Figure 14). 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) (Figure 14, 15); 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 (Stoffel *et al.*, 2013; Ballesteros Canovas *et al.* 2018). The coefficients of determination were slightly higher compared to those estimated for h_{tc}, provided that the number of PSIs was correlated to $h_{max,24}$ 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) (Figure 14, 15).

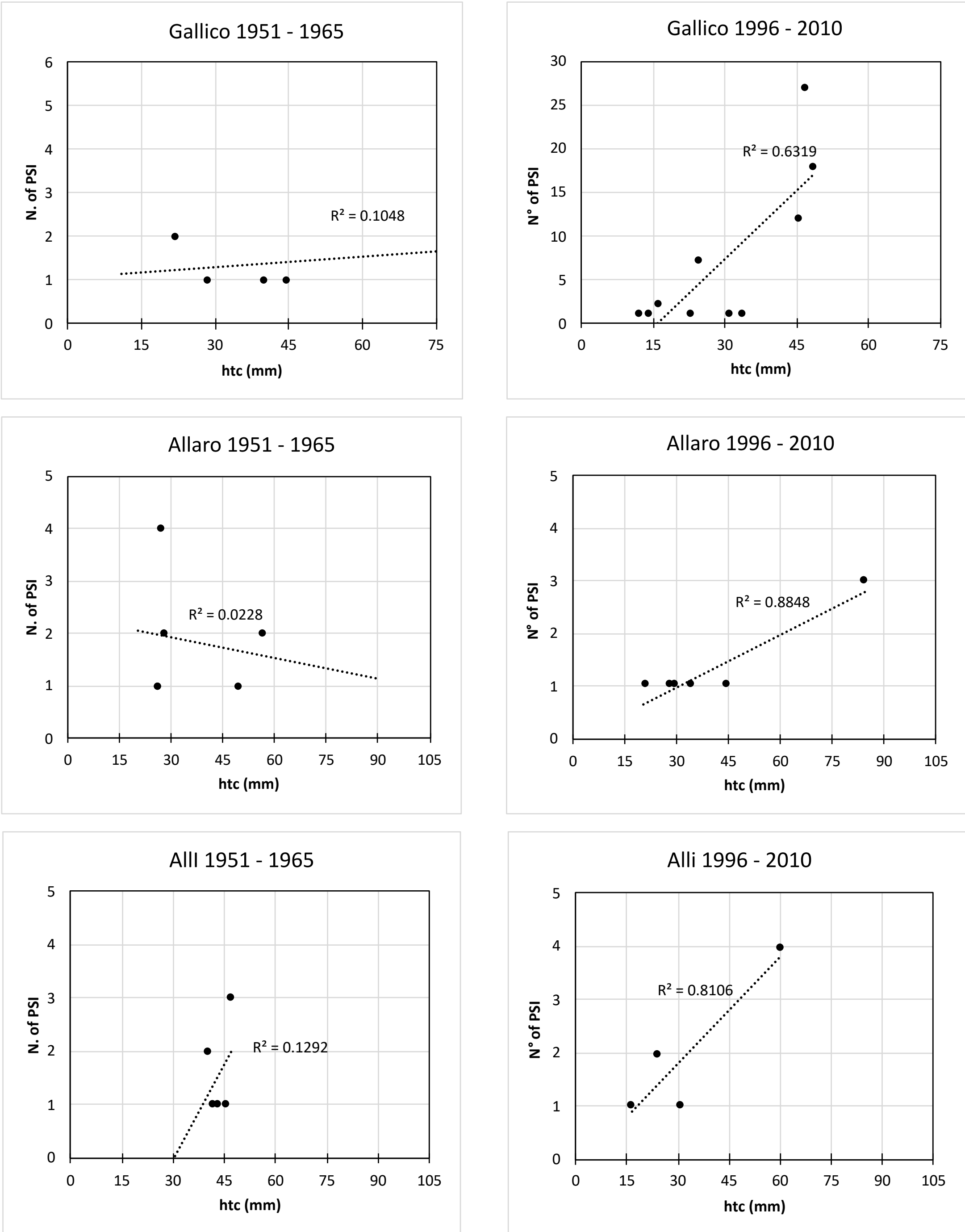


Figure 14. Linear regressions between the number of PSIs and critical rainfall depth (h_{tc}) measured in the Gallico, Allaro and Alli torrents for the time windows 1951–1965 and 1996–2010.

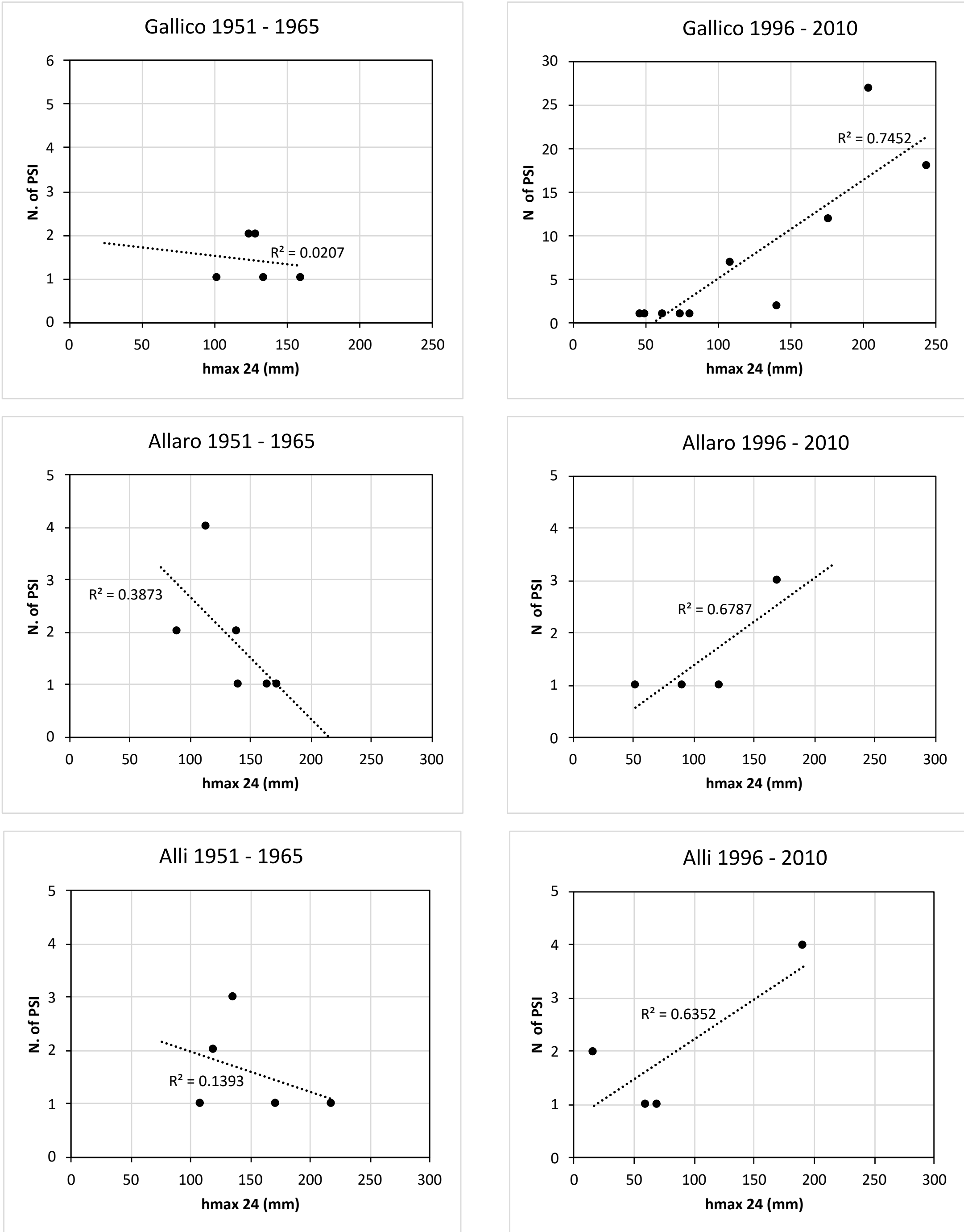
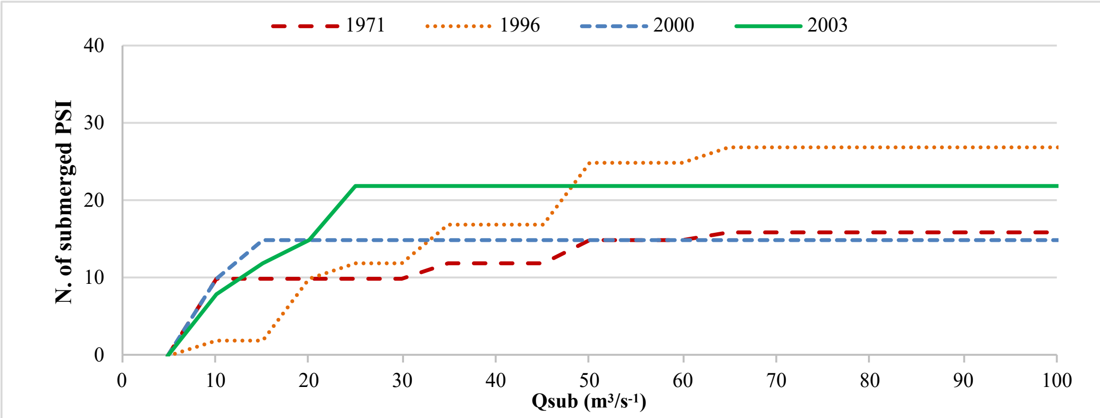


Figure 15. Linear regressions between the number of PSIs and maximum 24-hour rainfall depth (h_{max}) at Gallico, Allaro, and Alli torrents for the time windows 1951–1965 and 1996–2010.

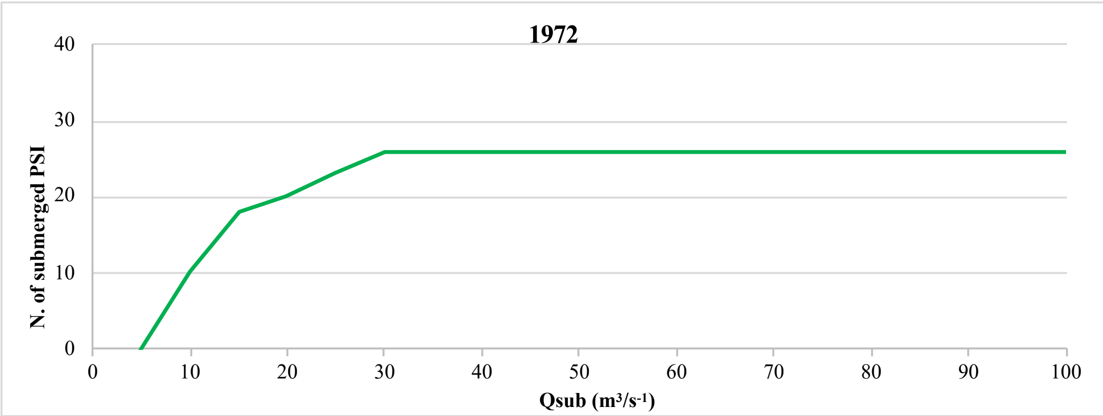
Step-backwater and rational methods application

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 (Figure 16 a–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).

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 5) 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 50^{th} percentile of the distribution of PSI deviations) of the deviation for this range (Figs. 16-17). The estimated peak discharges had a return interval of 5–30 years (Table 5).



(a)



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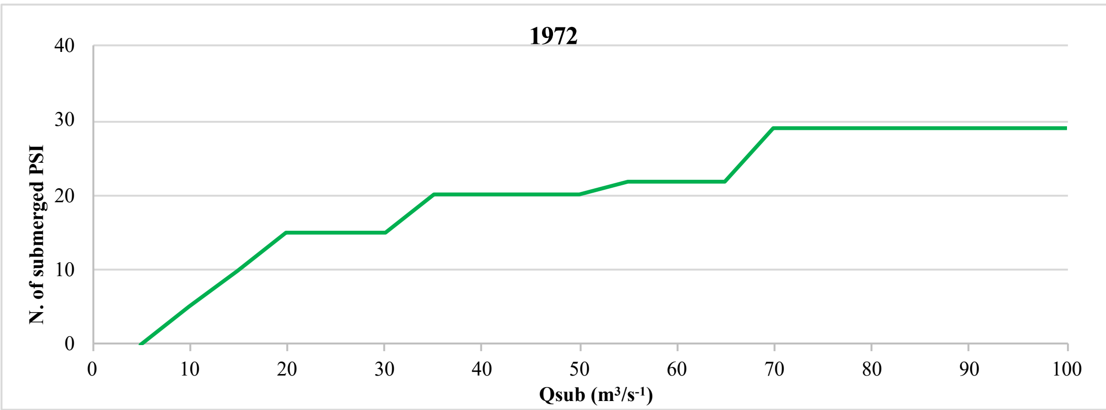


(c)

Figure 16. 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.

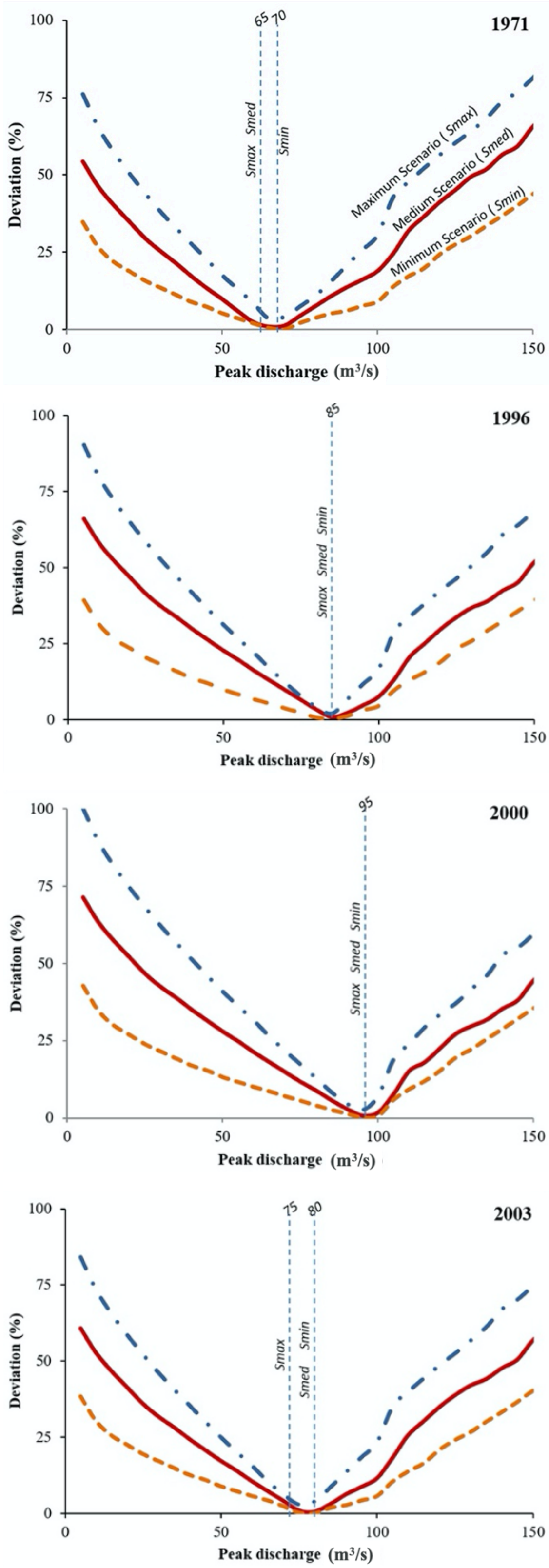
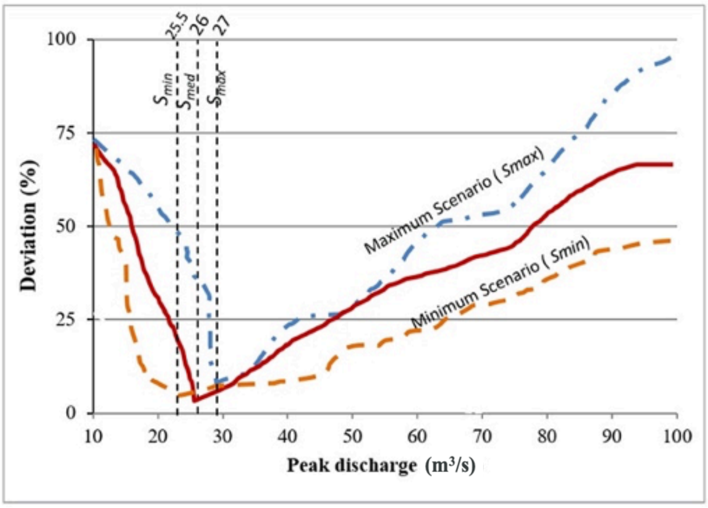
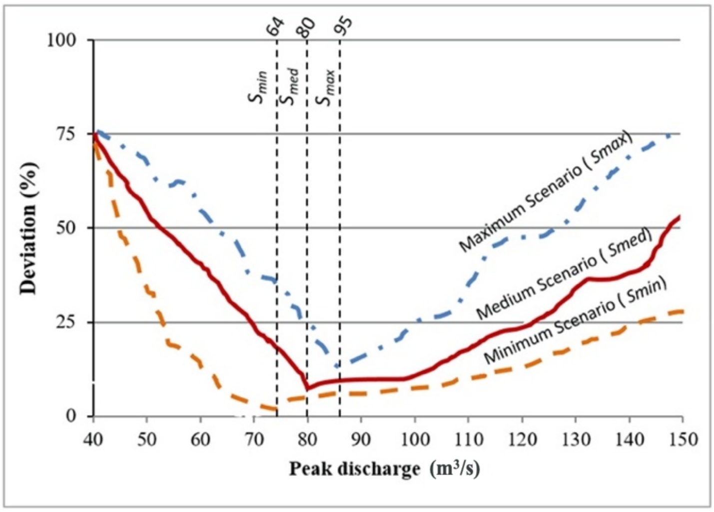


Figure 17. Estimation of the most reliable peak discharge value (calculated for the three scenarios, S_{min}, S_{med} and S_{max}, of the step-backwater method) of extreme floods in Gallico torrent.



(a)



(b)

Figure 18. 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 1971-1972 for the Allaro (a) and Alli (b) 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 5). 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 & 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) (Figure 18). 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 5).

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 5. 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	45,0	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 (Figure 19, Table 7) 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.

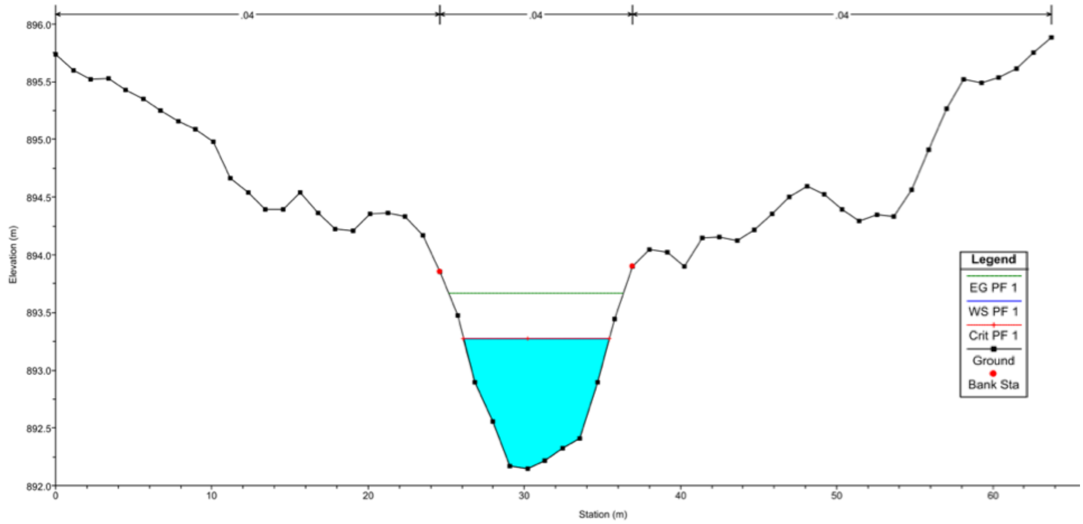
Table 6 reports water depth values measured in the three gauged catchments and related peak discharge derived from these measurements. Comparison of these peak discharge values and mean PSI height was based on 27 scars located in the vicinity of the gauging stations (upstream or downstream); the differences 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 6. Water depths measured in Allaro, Melito and Alli torrents and related peak discharges calculated from these values (flood event of 1971-1972).

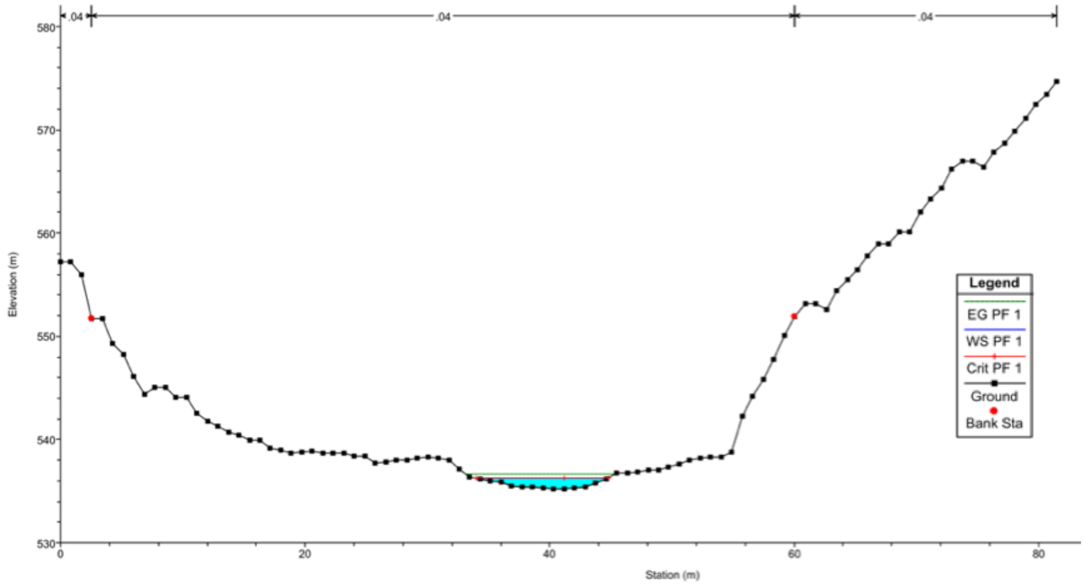
Catchment (location of the stream gauge)	**Area (km^2)**	**Measured water depth (m)**	**Measured peak discharge ($m^3 s^{-1}$) (*)**	**PSI height (mean ± std. dev.; number) (m)**
Allaro (Mongiana)	11.8	2.47	22	2.41 ±0.16 (n = 10)
Melito (Olivella)	11.2	2.29	49	2.54 ± 0.05 (n = 8)
Alli (Orso)	46.0	2.49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

(*) Data from VA.PI. (Versace *et al.*, 1989).

Differences between h_{PSI} and measured flood water depth (dH) increase with the rising distance of trees from the thalweg (Figure 20). Overall, we find correlations of R^2>0.50 between h_{PSI} and h_{SIM} for the flood of 1971-1972.



(a)



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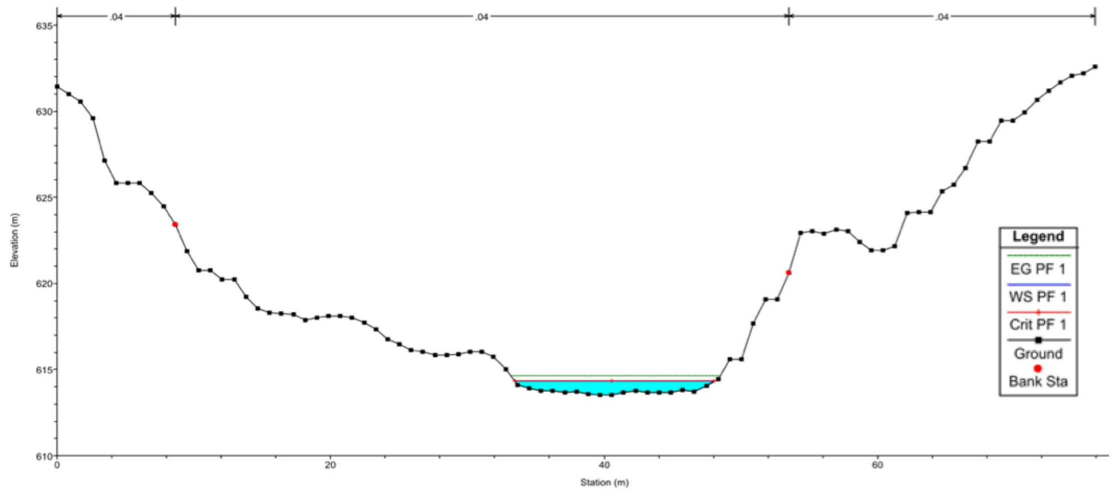

(c)

Figure 19. A sample of sections and simulated water depth by using HEC-RAS model for a) Allaro, b) Alli and c) Melito torrents.

Table 7 – Values of the water depth simulated by the HEC-RAS model (h_{SIM}), the PSIs height (h_{PSI}) for the Allaro, Alli and Melito torrents, for the event of 1971-1972.

Stable sections		h_{SIM} (m)	h_{PSI} (m)
Allaro (Mongiana)	1000	2.25	2.3
	900	1.68	2.46
	800	2.5	2.44
	700	1.78	2.34
	600	2.47	2.49
	500	1.32	2.52
	400	3.68	2.75
	300	3.49	3.76
	200	2.38	2.41
	100	1.31	1.36
Alli (Orso)	1000	2.5	2.37
	900	2.72	2.55
	800	2.8	2.84
	700	1.93	0.66
	600	2.5	2.00
	500	2.5	2.54
	400	2.5	2.00
	300	2.48	2.53
	200	2.6	1.90
	100	2.25	1.31
Melito (Olivella)	800	2.67	3.44
	700	2.39	2.33
	600	2.5	2.50
	500	2	1.15
	400	2.22	1.70
	300	2.3	2.10
	200	2.48	2.41
	100	2.35	1.46

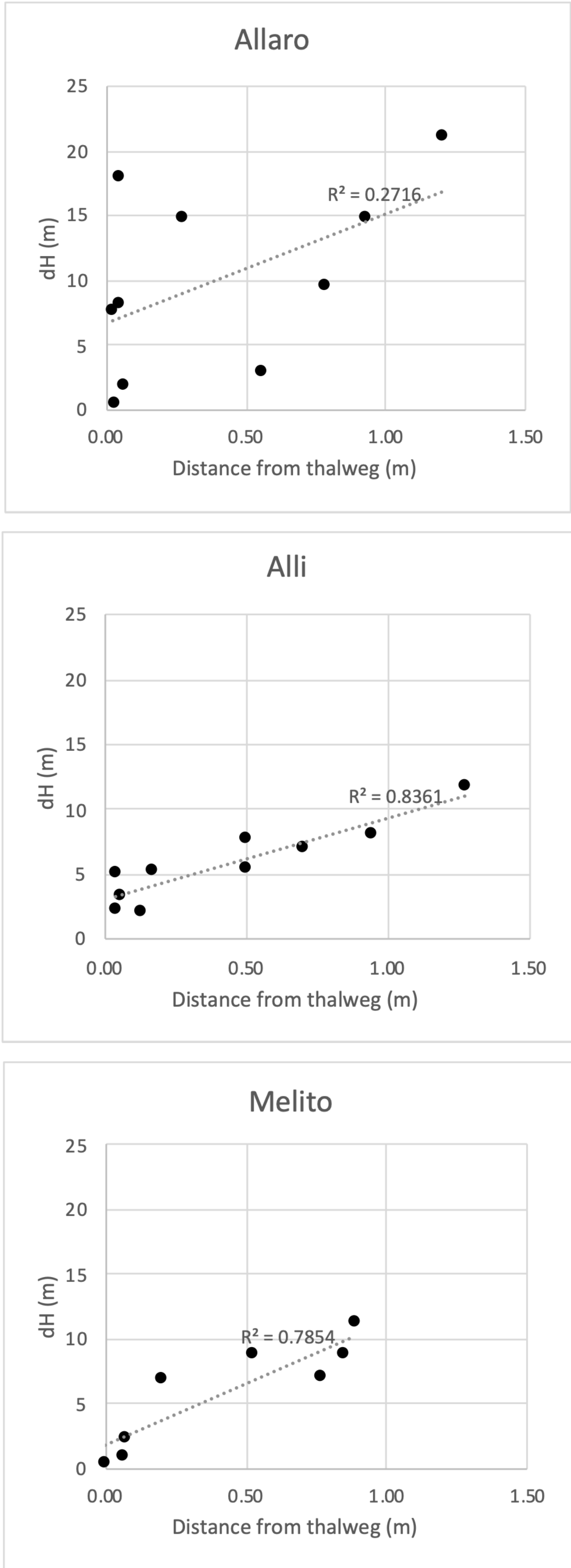

Figure 20. Linear regressions between *dH* and tree distance from thalweg for the Allaro, Alli and Melito torrents.

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 Cánovas *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 modelling 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).

CONCLUSIONS AND FUTURE PERSPECTIVES

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, existing methodologies in the fields of dendro-geomorphology were adapted 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.

The in-depth study of the issues discussed in this thesis work suggest the possibility of integrating the methodology in order to (i) analyse the multitemporal morphological evolution of streams (e.g., by comparing diachronic images), as an additional tool for the interpretation of PSIs; (ii) the role of erosion/deposition processes as an useful detailed information on the variability of channel morphology; (iii) investigate the geomorphological phenomena of catchments (e.g., gravitational movements) and to applicate semi-quantitative models to evaluate the sediments production, erosion and transport capacity, that can contribute to the formation of many PSIs.

Finally, the indirect analyses carried out considering only the geometric characteristics of the check dams, theoretically indicative of the spillways discharge capacity, and therefore, of the design flood (with a specific return period), have shown that such information, when considered "isolated", are insufficient in order to reconstruct the capacity of check dams. By proceeding in this way, in fact, the morphological variability of streams is not taken into account. However, the spillways size, suggest that more than to meet the need to dispose the expected flow rate, check dams were constructed only based on the width of the channel section. It would be interesting, therefore, to recover the original projects of the check dams and the relative hydrological studies taken into account, in order to deepen this aspect with further investigations.

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APPENDIX

For this thesis work, an in-depth study was conducted on the marks left on plants by flood flows (in the text, PSIs). Below, is a summary of the types of botanical evidences taken into account in the analyses conducted for the reconstruction of extreme flood events, and the relative references.

a) Corrasion scars (abrasion)

Figure A1

Figure A2

Figure A3

Figure A4

This type of scars is commonly found in tree trunks along the banks of a channel. Scars are the result of abrasions due to the impact of debris carried by high water, which damage the *cambium* (wood-producing tissue): this can lead to the interruption of radial growth at the point where the tree was struck. In subsequent years, the scar will become more and more covered with callus growth until the damaged parts are completely covered and the *cambium* will again be continuous around the trunk. Cross sections through the scarred portion of the trunk can yield the exact year of damage. Therefore, by coring the trees in correspondence of scars (up to their biological centre – pith) it is possible dating the peak flow responsible of the impact of debris with the plant.

b) Tilting trees in streamflow direction

Figure B1

Figure B2

Figure B3

The trees affected by a peak discharge are bent and inclined in a downstream direction, showing a deformation similar to that of wind-trained trees; some researcher calling this a "flood-trained" form (Lindsey *et al.*, 1961). As long as 25 years after an event, the trunks of trees are still bent and inclined in a downstream direction and generally have scars on the upstream side. Eccentric annual growth can be seen in stem wood where one side of the trunk produces more wood than another.

Abruptly tilted trees show an eccentricity of the growth rings, with respect to the vertical, due to the deviation of the pith from the centre of the stem; this phenomenon causes a succession of rings that show a "compression" in one direction and an "expansion" in the other (Figure B3).

The date of the onset of the eccentric growth is usually within 1 year of the event that caused the tilting, depending on the season and severity of tilting. It is possible to date the damaging event by reading and analysing the growth rings on the cross sections of the stem.

c) Adventitious sprouting along the felled trunk

Figure C1

Figure C2

Trees that have been damaged by high water generally can be felled, bent over or partly uprooted: that severe damage and burial are not necessarily lethal. In fact, trees develop one or more vertical sprouts on the upper side of the part of the inclined parent trunk that protrudes from the ground. This trunk, like those of all water-felled trees, is aligned nearly parallel to the direction of streamflow.

The adventitious roots commonly start to grow from branches still attached to trees when the branches come into contact with moist soil (Kramer and Kozlowski, 1960), and the fallen tree continues to live., resulting in the growth of adventitious sprouting along the parent stem.

The simple form consists of a vertical sprout growing from an older inclined trunk. the stub of the parent trunk consists of a protrusion of rotten wood that may be only partly covered with wound tissue. The roots are upstream, and the trunk is inclined in a downstream direction. The L-shaped form and differences in texture of the bark persist for a long period of time.

Just as a scar on the side of a trunk, it is possible to determine the year that the tree was felled.

The vertical sprouts start to grow from the inclined trunk during the first growing season after the tree was felled; thus, a count of the annual rings in a core from the base of the sprout that includes the outer- and inner-most rings tells the number of growing seasons since the tree was knocked down.

These sprouts begin growing within 1 year after tilting and provide an excellent line of evidence (Hupp 1983) when replicates are found, for a particular date of an event.

d) Group of trees of the same age grown along the longitudinal direction of the channel

Figure D1

Figure D2

Figure D3

Figure D4

In this case, at the base of the sprouts there are rotten stumps, which can be visible with a little digging in the centre of the area surrounded by the circle of sprouts; or the sprouts may appear as closely grouped trunks, seemingly growing out of the ground, until an excavation around them reveals that they are all connected to the same root system. Such stumps have been buried during subsequent floods. This growth form cannot be distinguished with certainty from sprouts growing from a sawed stump; but sprouts growing from rotten stumps in an area in which many trees of the same age are sprouts growing from inclined trunks, probably date from a severe flood.
It is possible to determine the age of the plants, structured in group of equal in age trees, with the method of coring on a variable number of individuals (≥ 25% of the total formation identified). This allows to trace the date of the peak discharge responsible.

e) Some stumps buried by alluvium deposited during subsequent floods

Figure E1

Figure E2

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