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Evaluating the effects of check dams on channel geometry, bed sediment size and riparian vegetation in Mediterranean mountain torrents

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ABSTRACT

In mountain streams possible negative impacts of check dams on soil, water and riparian vegetation due to check dam installation can be noticed. In spite of the ample literature on the qualitative effects of engineering works on channel hydrology, morphology, sedimentary effects and riparian vegetation characteristics, quantitative evaluations of the changes induced by check dams on headwater dynamics are rare.

In order to fill this gap, this study has evaluated the effects of check dams located in headwaters of Calabria (Southern Italy) on hydrological and geomorphological processes and on the response of riparian vegetation to these actions. The analysis has compared physical and vegetation indicators in transects identified around check dams (upstream and downstream) and far from their direct influence (control transects).

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). The actions of the structures on torrent longitudinal slope and biodiversity of vegetation were less significant. The differences on bed profile slope were significant only between upstream and downstream transects. 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 before check dam construction. Moreover, simple and quantitative linkages between torrent hydraulics, geomorphology and vegetation characteristics exist in the analysed headwaters; 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.

Keywords: headwater; channel morphology; torrent hydraulics; bed profile; vegetation biodiversity; transects.

1. INTRODUCTION

Mountain streams, and particularly headwaters, are very delicate ecosystems, since they are affected by many disturbance factors, such as hydrological, geomorphological, and human impacts (Wohl, 2017; Rodrigues et al., 2017). Furthermore, across diverse hydro-climatic regions, headwaters exhibit high spatial and temporal variability, which strongly influences the river ecosystem (Marmontel et al., 2018).

Headwaters represent a natural hazard, because of the rapid increase in flow hydrographs, potential massive bedload transport and accelerated erosional processes that occur during high-magnitude flood events (Rickenmann, 1997; Galia and Škarpich, 2017). In Mediterranean zones, headwaters, in response to specific local conditions (e.g. frequent and intense rainstorms, small basins, steep slopes, Zema et al., 2014), are prone to high magnitude flash floods with high erosive power, often causing hydro-geological instability and disruption (Fortugno et al., 2017). In these contexts (such as in Southern Italy and Spain, as reported for instance by Bombino et al., 2007, and Boix-Fayos et al., 2007) the need to control 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.

Two widely applied soil conservation strategies in Mediterranean environments are reforestation and the construction of check dams in rivers and streams (Boix-Fayos et al., 2008). Check-dams (in general less than 5 m high, Castillo et al., 2006) are built in staircase like sequences of cemented, boulder, or wooden grade-control structures (Lenzi and Conesa-García, 2013). The main purposes of check dams are to serve as small sediment storage structures and/or to add flow resistance (reducing channel slope and increasing bed roughness), in order to stabilize the channel bed and the adjacent hillsides (Conesa-Garcìa et al., 2007).

In mountain streams, where the human impact is low, the installation of check dams modifies the natural evolutionary processes and may have noticeable influences torrent hydro-morphology and eco-hydrology. More specifically, in order to establish equilibrium conditions in the torrents, check dams decrease the longitudinal profile slope, thus slowing water and sediment movement along stream channels (Bombino et al., 2009). This action plays local effects on cross section shape, surface and subsurface sediments, which, on their turn, reflect also on structure and cover of riparian vegetation and even on its biodiversity (Bombino et al., 2014). Moreover, these effects are different between zones close to the check dams and those less disturbed (far from them) and between upstream and downstream of check dams.

However, possible negative impacts on sediment, water and vegetation due to check dam installation also in the less disturbed headwaters can be noticed. As a matter of fact, some authors state that check dams produce important negative effects like downstream scouring, which changes the stream channel, hydrological regime and morphology (e.g. Castillo et al. 2007; Boix-Fayos et al. 2007; Conesa-García and García-Lorenzo, 2009; Ramos-Diez et al., 2016b; 2017). Moreover, check dams are usually not paid any further attention once they are built and their role and benefits are overlooked (Bombino et al., 2008; Ramos-Diez et al., 2016b). There is, thus, a need to evaluate the efficacy of these works and the evolution of regulated channels over time, especially in those projects in which the role of check dams is questioned (Ramos-Diez et al., 2016b).

Eminent and ample literature exists, which has widely debated the effects of check dams on hydrology (e.g. Norman et al., 2016; Guyassa et al., 2017), morphology (e.g. Boix-Fayos et al., 2007; Gao et al., 2016; Fortugno et al., 2017), sedimentary effects (e.g. Ramos-Diez et al., 2016a; 2016b; 2017a; 2017b) and riparian vegetation characteristics (e.g. Bombino et al., 2006; 2008; 2009; 2014). However, as far as now, the actual impact of check dams is still not well known (Castillo et al., 2007), because their effects on physical processes and vegetation characteristics in delicate environments, such as headwaters, are not yet completely understood or, at least, have often been studied disjointedly by qualitative approach based on field observations. In other terms, we feel the lack of an objective evaluation, which should measure the torrent response to the modifications induced by check dams on hydrological regimes, morphological changes, erosion/sedimentation processes and torrent ecology. As regards this latter, in order to better understand the global dynamics of headwaters (considering the large number of influencing variables), more attention should be paid to the effects of control works on riparian vegetation, being one of the most important indicators of soil quality, and river health and functioning. This evaluation is necessary in order to inform the development of design criteria minimising the check dams impacts into fluvial dynamics and define the desired state after restoration, preliminary to the correct restoration project design (Henry and Amoros, 1996).

In order to accomplish this task, this study evaluates the effects played by check dams located in headwaters of Calabria (Southern Italy) on hydrological and geomorphological processes and the response of riparian vegetation to these processes. More specifically this paper: (i) analyses the differences between the indicators surveyed upstream, downstream and far from the local influence of check dams; (ii) looks for correlations between couples of indicators, able to quantify the reciprocal influence of an indicator on another; and (iii) identifies statistical similarities between such locations along the torrent. The quantitative results are explained by linkages with physical and vegetal processes acting in the studied reaches.

2. STUDY WATERSHEDS

The torrents of Calabria (Southern Italy) are steep, short and seasonally-flowing mountain streams with small catchments, locally known as *fiumara* (Bombino et al., 2009). These water courses have a torrential regime, whose response to the hydrological stress produces high-magnitude flash floods and erosive events (Fortugno et al., 2017).

The investigation was carried out in the mountainous reaches (“headwater”) of four fiumaras (Figure 1): Allaro (A), Torbido di Gioiosa (TG), which drain towards the south east, and Sant’Agata (SA) and Gallico (G), which drain towards the south west (Figure 1). The four torrents rise at over 1200 m above sea level and flow through deep narrow valleys (mountain reaches) and wider floodplains downstream (valley reaches), discharging (main stream lengths from 17 to 26 km) into the Ionian (A, TG and SA) or Thyrrenian sea (G). Their watershed areas vary from 56 (G) to 161 (TG) km^2 (Table 1).

Many studies based on the “landscape ecology” approach (Allen and Hoekstra, 1992) and the "river continuum concept” (Raunkiaer, 1934), suggest a longitudinal subdivision of the river environment, from the source to the mouth, in order to take into account the spatial and functional relationships between biotic and abiotic components of the water courses. The longitudinal subdivision of the river environment defines zones of homogenous conditions in terms of climatic (e.g. temperature and precipitation), geomorphological (e.g. channel geometry, hydrological regime, bed sediment size) and vegetal (e.g. floristic composition) factors (Bombino et al., 2006; 2007). This prior subdivision of the torrents identified "homogenous" mountain, middle and valley reaches. In order to control for factors other than the impact of engineering structures, the study was conducted within single mountainous homogeneous torrent reach (Bombino et al., 2008), hereinafter indicated as "headwaters".

2.1. Climate and hydrology

The region of Calabria is located in the extreme southern part of Italian peninsula. Its 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), according the Koppen-Geiger classification (Kottek et al., 2006). In the headwaters winters become very cold and summers are cool, with a total annual precipitation between 1351 (SA) to 1780 (A) and mean annual temperatures between 9.9 (G) and 11.2 (A) °C (Table 1). Snow is common only in few days or one-two weeks throughout the year and mainly in the upper sub-reaches.

The mountain reaches 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 (Table 1). The flow regime (intermittent in the lower-order streams and perennial in the main reach) is controlled by sudden storms and, once every almost two or three years, by episodic and intense flash floods. In these streams flash floods with longer recurrence intervals (5-10 years or more) have the major effects on channel morphology and ecology; 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 and Walling, 1973; Richards, 1982) with no heavy geomorphic adjustments on bed longitudinal profile (Fortugno et al., 2017). However, extreme events (such as heavy flash floods with high recurrence times) thoroughly remodel the torrent morphology by transporting along the profile the sediment eroded on hillslopes and delivered to the channel.

2.2. Morphology, land use and soil

The mountain reaches of the four studied torrents are characterised by: (i) catchment areas between 10 (TG) and 48 (A) km^2; (ii) main channels from 3.7-km (TG) to 7.0-km (SA) long; (iii) narrow sections from 10.5-m (TG) to 34-m (G) wide; (iv) thalwegs with a mean longitudinal slope from 9.2% (A) to 11.4% (SA) (with sub-reaches getting 20%) (Table 1).

According to the CLC classification of 2016, the land use of the four mountain reaches is predominantly forest (mainly *Fagus sylvatica* L., *Pinus nigra ssp. laricio var. calabrica* and *Abies alba* Mill.) and shrub, which covers from 77% (SA) to 93% (G) of the headwater area. Other land uses in the headwaters are intensive crops (on average 20% in the four basins area) and complex crop system (on average about 5%) (Table 1 and Figure 2).

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 and Figure 2). 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, 1993).

2.3. History of watershed management

The management strategy adopted in the majority of torrents of Calabria provided, beside heavy reforestation works, the construction of series of check dams at the middle of the twentieth century, in order to primarily stabilize the longitudinal bed profile by graded sub-reaches (with a longitudinal slope lower than the original profile) and secondarily consolidating torrent banks from lateral erosion (Fortugno et al., 2017).

Currently, the main channel of the studied headwater shows the presence of 5 (headwater "TG") to 20 (G) staggered check dams (from 2.5-m to 10-m high). The structures are made of concrete or stone and concrete and at present are almost completely filled up with sediments. At a later date (predominantly the 1970s), additional smaller check dams (about 3-m high) were built to prevent local scouring downstream of the existing check dams. A series of sediment collectors was created and, in successive floods, the channel bed immediately upstream of the check dams was filled. 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).

3. METHODS

3.1. Identification of check dams and survey transects

In each headwater of the four torrents five check-dams, ranging in height from 3 to 4.5 m, were selected. All were 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.

Following the approach proposed by Bombino et al. (2006), five reaches (one for each headwater, containing a check dam) were identified and studied. In every reach three transects were located, of which two positioned in proximity from check-dams (upstream and downstream) and the third one positioned in an intermediate zone between the dams (assumed as control zone). Upstream (henceforth indicated by the letter U) and downstream (D) transects were located at the height of the check dam away from the dam, while the minimum distance of the intermediate transect from the dam was defined by the siltation basin. The intermediate transects represent sites less disturbed by the presence of the check dams and thus were assumed as control (and henceforth indicated by the letter C), since they were positioned at sufficient distance and the local influence of the check dam on the channel can be considered negligible (Bombino et al., 2006). In other words, between two consecutive check dams, the C transect was located within the sub-reach confined between the upper limit of the sediment wedge of the downstream check dam and the lower limit of the incised channel of the upstream structure, where the local effects are less evident.

3.2. Selection of physical and vegetation indicators

At each transect we studied physical and vegetation local characteristics of the channel. As physical characteristics, we considered channel morphology, hydraulic regime of the water stream and bed (surface and sub-surface) sediment parameters, while, as vegetation characteristics, development (that is, extension, structure and spatial distribution) and biodiversity (that is, species richness, relative abundance and degree of integrity) of the riparian vegetation were focused (Table 2). In order to give a quantitative approach to our study, these physical and vegetation characteristics were studied through as many synthetic but representative parameters (henceforth indicated, in general terms, as "indicators"), calculated based on field surveys and measurements (Table 2).

For active channel morphology indicators, the “width to depth ratio” (w/d, [m m^{-1}]) of the transect section and the local slope (LS, [%]) of the longitudinal profile of the thalweg were chosen. The "w/d" indicator must be considered as a parameter indicative of the transect shape, because it is lower in narrower and deeper cross sections (V-shaped, typical of downstream transects) and larger and less incise channels (U-shaped, typical of upstream transects) (Conesa-García and García-Lorenzo, 2010). As indicator of the torrent hydraulic regime, the discharge (q) per unit width required to fill the active channel (henceforth called "specific discharge") was identified.

The characteristics of the torrent bed material were studied adopting as indicators the median particle size of surface sediments (SD_{50}, [mm]) and the percentage of subsurface finer sediment (SSF, [%]). This latter was taken into account, because of the importance of finer sediments for moisture retention (e.g. Hillel, 1982) in sub-surface of beds of these ephemerally-flowing water courses; here, the main root zone of many riparian species develops.

As regards the indicators related to the riparian vegetation, its extension and structure were measured by the two synthetic parameters proposed by Bombino et al. (2006), the Global Canopy Cover (GCC, [%]) and the Weighted Canopy Height (WCH, [m]). In summary, GCC is 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. GCC values fall in the range 0% to 100%. WCH is defined as the sum of the products of the average height of the individual layers (herbaceous, shrub, tree) and the corresponding canopy cover. The spatial distribution of the riparian vegetation was measured by the Coefficients of Variation of the two parameters above mentioned (CV_{GCC}, [%], CV_{WCH}, [%]), which explain the transverse variability of extension and structure; more specifically, if CV_{GCC} and CV_{WCH} are close to zero, there is a noticeable uniformity in the vegetation cover and height in the cross section, while, if these coefficients are high (100% or more) the extension and structure of riparian vegetation along the transect must be considered less or non-uniform.

As outlined above, the biodiversity of riparian vegetation was quantified by species richness, relative abundance and degree of integrity of the riparian vegetation. In order to quantify these characteristics the following indicators were adopted:

- the α-diversity index (H_α), proposed by Hill (1973), which measures the species richness for $\alpha = 0$ and the relative abundance for $\alpha = 2$ (more specifically, H_0 increases with species richness, while H_2 is close to zero in the case of dominance of a few species and is equal to one when plants are equally distributed among the different species within the surveyed area, i.e. in the case of species evenness) (Simpson, 1949);
- 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.

3.3. Survey and analysis methods

In order to calculate the above mentioned indicators, field surveys were carried out in the studied headwaters at U, D and C transects at different date during a calendar year. Prior of the measurements of channel morphology and hydraulics, the limits of the ‘active channel’ - which in these ephemeral systems includes the contemporary riparian zone (ecotone) - were identified. To this aim, the following indicators were adopted: a change in vegetation from riparian to terrestrial species (this was usually clearly defined by changes in the tree species); distinct breaks in slope and/or particle size; the position of scour or trash lines (Figure 2). The most consistent measure proved to be the change in vegetation species and this was refined using the other indicators wherever they were identified (Bombino et al., 2009).

The width (w) and maximum depth (d) of the active channel were measured in correspondence to the hypothetic free surface of the torrent stream and then the w/d ratio was calculated. The local slope (LS) of the channel longitudinal profile was measured by a total station (Pentax R-400 model). The hydraulic indicator q was calculated by the following equation:

$$q = Q/\overline{w} \; [m^3\,s^{-1}\,m^{-1}] \qquad [1]$$

where $\overline{w}$ [m] is the ‘mean’ width of the transect and Q [m^3 s^{-1}] is the uniform flow of the channel, calculated by Manning's equation. On its turn, $\overline{w}$ was calculated as the ratio between the cross-sectional area of the active channel (A, [m^2]) and its maximum depth (d, [m]) and the roughness coefficient (n) of Manning's equation was calculated from field estimates (Figure 2), based on the values for river channels suggested by Chow (1959). The flow level entering Manning's equation was considered to be equal to the maximum depth (d) of the active channel.

Postponing detailed information about sediment analysis to previous works (Bombino et al., 2008), the indicators related to channel bed sediments were evaluated by two distinct methods as summarised below.

The surface bed material was sampled in situ every 50÷60 cm along each transect. On each sample the photographic technique (Adams, 1979) was used to measure the intermediate B-axis of particles larger than 2 mm, since sediments were quite coarse and then this technique was considered suitable. Form the particle distribution obtained for each sample, the median particle size of surface bed material (SD_{50}, [mm]) was calculated for each transect (Bombino et al., 2008). Zones with dense vegetation were excluded from positions of photographs. In such occasions, we moved slightly downstream or upstream of this position.

As regards the sub-surface sediments, the samples (four in the U transects, and two in each D and C transects, given the lower width of these latter) were taken at 0.30-m depth, in which the main root zone of many riparian species develops. In the laboratory, the finer sediment fraction (less than 0.25 mm) was separated from the bulk sample by sieving and was expressed as the percentage of the finer sediment by weight. The average percentage of subsurface fine sediment (SSF, [%]) was calculated for each transect.

The vegetation complexes were classified in terrestrial and riparian species according to their floristic composition and based on the ecological habitus of each species. More information about the species detected in the studied watersheds can be found in a previous paper of the same authors (Bombino et al., 2014). To calculate the indicators related to characteristics of riparian vegetation, sample areas were identified across the transects. At each sample area (with a minimum representative area of 50 m^2) vegetation parameters (number of species and plants for both N and A species, canopy cover and height of each species) were surveyed according to the methods developed by Bombino et al. (2006).

As regards the biodiversity indicators, the values of H_0 (measure of the species richness) and H_2 (dominance index) were calculated using Rényi’s function (O’Neill et al., 1988; Li and Reynolds, 1993) applied to the frequency of plants belonging to each species found in each transects. The Ns_A/Ns_N parameter (indicator of the degree of integrity of vegetation) was simply the ratio between the number of alien (A) and native (N) species surveyed in each transect. Both exotic species and the terrestrial complexes falling within the active channel were considered among the alien species.

All the vegetation surveys were carried out in the same season in all the studied watersheds, in order to avoid seasonal differences in development and composition of riparian vegetation (mainly for the herbaceous species).

3.4. Data processing techniques

Prior to apply other processing techniques, 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. To differentiate the levels of significance, both $p < 0.01$ and $p < 0.05$ were adopted.

Then, 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 by converting data to zero mean and unit variance. The correlation coefficients (r) measured the explanatory capacity of the linear regressions. Finally, 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 our case the indicators). As similarity measure between two transects i and j, Pearson's correlation distance $D(X_i, X_j)$ was used, calculated by the following expression:

$$D(X_i, X_j) = \frac{1 - r_{ij}}{2} \qquad [2]$$

where:

$$r_{ij} = \frac{\sum_{k=1}^{N} (x_{ik} - \bar{x}_i)(x_{jk} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{N} (x_{ik} - \bar{x}_i)^2 \sum_{k=1}^{N} (x_{jk} - \bar{x}_j)^2}} \qquad [3]$$

being:

- r_{ij} the Pearson’s correlation coefficient between the transects i and j;
- X_i and X_j the vectors of the indicators for the transects i and j;
- x_{ik} and x_{ik} the indicators k of the transects i and j;
- $\bar{x}_i$ and $\bar{x}_j$ the arithmetic means of the indicators x_{ik} and x_{ik};
- N the number of the indicators.

Transects grouping through AHC analysis were reported in a dendrogram. The vertical axis of the dendrogram indicates the distance or dissimilarity between clusters, whereas the horizontal axis represents the different transects. Each vertical line indicate a cluster of transects. The entropy criterion was chosen in order to identify the number of similar clusters of transects, shown in the dendrogram by the position of the dotted horizontal line on the vertical axis (clustering level, Zema et al., 2015).

All statistical analyses were performed using XLSTAT® release 2017.

4. RESULTS

4.1. Effects of check dams on physical indicators

Upstream of check dams the transects showed a w/d ratios on the average about 3-fold and 4-fold the values measured in downstream and control zones, respectively: in U sub-reaches the channel width was 20-fold its depth and this ratio decreased to 7.6 and 5.0 in C and D transects, respectively (Figure 3). Compared to the conditions before their construction, the transects widths were increased on average by 50-60% upstream and reduced by 20-25% downstream of the check dams, respectively.

Due to check dam installation, the longitudinal slope (LS) of the channel, close on the average to 2.3% in C zones (undisturbed reaches), decreased to 1.8% in the upstream transects and increased to 3.2% downstream: on the average, the longitudinal profile in D sub-reaches was steeper by 36.4% than U zones (Figure 3). As shown by Kruskal-Wallis test, channel shape (indicated by w/d) of U transects was significantly different (at $p < 0.01$) from D and C zones; the local longitudinal slope (LS) was significantly different (at $p < 0.01$) only between U and D transects (Table 3).

The specific discharge per unit width (q) filling the active channel, estimated by Manning's equation, was significantly different for the three groups of transects, since the active channel width (w) and depth noticeably changes among U, D and C reaches (Table 3). In U and D transects q was on the average one third and 2-fold, respectively, the value estimated in C transects (Figure 3).

In C transects the median diameter of bed surface material (SD_{50}) and the mean content of sub-surface finer sediment (SSF) were 42.1 mm and 22.9%, respectively. As expected, mean SD_{50}

became lower in U transects (29.2 mm) and higher in D sub-reaches (92.2 mm), while mean SSF increased upstream of check dams (31.5%) and decreased downstream (14.3%) (Figure 3). The differences for the surface and subsurface sediment indicators were significant at $p < 0.01$ among all groups of transects (Table 3).

4.2. The response of the riparian vegetation to the presence of check dams

Weighted cover (GCC) and height (WCH) of riparian vegetation, representative of the whole transects, were on the average 55.4% and 3.1 m in U transects, 38.8% and 2.1 m in D zones and 49.9% and 2.7 m in C sub-reaches. Compared to these latter undisturbed zones, the extent of riparian vegetation was higher (by 11.0%) in the U transects (but not significantly different at $p < 0.01$) and lower (by 22.2% and in this case significantly different) in the D zones. Also the structure of riparian complexes was found to be higher in U sub-reaches (+15.2%, but not significantly different, $p < 0.01$, from C transects) and significantly lower (-24.2%) in D zones (Figure 3 and Table 3).

In the C sub-reaches mean CV_{GCC} of 32.7% and CV_{WCH} of 28.8% were detected; in U transects CV_{GCC} and CV_{WCH} were halved (15.7% and 14.4%, respectively), while, in D zones, CV_{GCC} was lower (26.9%) and CV_{WCH} was higher (33.8%). The differences in transverse distribution of riparian vegetation along the transects were significant ($p < 0.01$) between U zones and the other groups of transects (D and C), but not between D and C zones (Figure 3 and Table 3).

As regards the biodiversity of riparian vegetation, U and C transects showed the same species richness (mean H_0 of 3.4 and 3.2, respectively) and relative abundance (mean H_2 of 3.0 and 2.9); lower values were measured for D sub-reaches ($H_0 = 2.9$ and $H_2 = 2.5$). The degree of integrity of vegetation (Ns_A/Ns_N) was on the average higher in U transects (0.21) and lower in D zones (0.08) compared to the C sub-reaches (0.17). The differences in the biodiversity indicators were significant only for the Ns_A/Ns_N indicator and only between D transects and the two other groups (U and C) (Figure 3 and Table 3).

4.3. Relationships between vegetation and physical properties

Pearson's correlation matrix showed interesting quantitative associations both across categories (hydro-morphology, sediment and vegetation) of indicators surveyed in the transects and, within each category, among couples of individual indicators; the most important mathematical relationships are summarised below.

As regards the associations between physical indicators - always significant at $p < 0.01$ ($|r| > 0.518$), except for the association LS - w/d, - we found that q was inversely correlated ($r = -0.729$) to w/ and SD_{50} was directly correlated with q ($r = 0.775$); reverse correlation was found between SSF and q ($r = -0.776$) and direct between SSF and w/d ($r = 0.836$) (Table 4).

Concerning the quantitative relationships among the characteristics of the riparian vegetation and the physical indicators, we found: (i) significant correlations between GCC, WHC and their CVs on one hand and w/d ($|r| > 0.752$) on the other hand; (ii) weaker correlations between the vegetation indicators and q, but always significant ($|r| > 0.530$), except for the correlation CV_{GCC} - LS ($r = 0.421$); (iii) fair correlations between GCC ($r = 0.814$), WCH ($r = 0.821$), CV_{GCC} ($r = -0.814$) and CV_{GCC} ($r = -0.632$) with SSF; (iv) the weakest correlations among the vegetation characteristics and SD_{50} ($|r| < 0.649$). No correlation was found between CV_{GCC} and SD_{50} ($r = 0.337$) (Table 4). The quantitative association among the biodiversity parameters and the other (physical and vegetal9 indicators were always weak ($|r| < 0.419$), except for some relationships between Ns_A/Ns_N on one side and q, SD_{50}, SSF, H_0 and H_2 on the other side ($|r| < 0.523$) (Table 4).

4.4. Analysis of similarities among groups of transects

AHC analysis identified three groups of transects by a high level of similarity. The first group, indicated as C_1 in Figure 4, included all U and C transects, but also six D sub-reaches; the majority of D transects (globally 14 out of 20) fell into the two other groups (C_2 and C_3) (Figure 4).

5. DISCUSSIONS

Our study compared the hydro-morphological and sediment calibre indicators (w/d, LS, q and SD_{50}, SSF) surveyed close to the check dams - immediately upstream and downstream - with those measured in less disturbed zones (assumed as control sub-reaches). These comparisons confirmed by a quantitative approach where and how much the control works significantly change cross section shape, hydraulic regime and bed sediment characteristics of headwaters. A conceptual scheme of the channel evolution and vegetation dynamics of Mediterranean headwaters regulated by check dams (before and after construction) is sketched in Figure 5. Below the physical and ecological processes governing this headwater dynamics are analysed and explained by a quantitative approach.

First of all, as regards the channel morphologic adjustments, upstream of check dams, thanks to the sediment accumulation behind the wall, the bed longitudinal profile aggradates (lower LS), the cross section enlarges (higher w) and the water stream is laminated (lower d) (Simons 1979; Leopold et al. 1964; Shieh et al., 2007). These results match findings of the previous study of Zema et al. (2014), who, carrying out a morphological and sedimentary analysis close to 10 check dams installed in one (Sant'Agata torrent) of the same headwaters, noted that the control works play a function of bed stabilization (due to the longitudinal slope reduction) and flood lamination (because of the wider channel section). Also Liu (1992) reported that the stream reaches behind each check dam increase in width. According to the same Author, theoretically the stream power is positively related to channel gradient and flood discharge, but negatively related to channel width. Therefore, after the installation of these check dams, the stream power is significantly reduced. The capacity for sediment transport is also decreased and channel erosion is prevented (Liu, 1992).

Conversely, downstream of the check dams, the erosive power of the stream scours and shrinks the channel, which shows a more incised and narrower section (higher d and lower w), leading locally to a steeper longitudinal profile (higher LS). Also Boix-Fayos et al. (2007) found downstream of the check dams lower width/depth ratio than upstream and fine sediments and vegetation present only on the flood plains or bars. Low width/depth ratios indicate erosion downstream of the check dam, due to the high erosive power of water without sediment (which has been trapped by the structure) and to the erosive power of the water falling from the top of the dam (Boix-Fayos et al., 2007). Furthermore, the contrasting processes acting upstream and downstream of check dams were highlighted by Hooke and Mant (2000), which showed an increase in channel erosion downstream and, in contrast, depositional processes occurring upstream. In these latter sites sedimentary wedges develop up to the achievement of the lower equilibrium channel slope and lead to a local decrease in SD_{50} of the surface bed sediments (Galia et al., 2016; Boix-Fayos et al., 2007). Overall, the sequences of bed sills and check dams decelerate or interrupt the sediment connectivity, especially coarser bed fractions. This often implies the downstream narrowing and incision of the channel and the downstream coarsening of the bed sediments (Gaudio et al., 2000; Martín-Vide and Andreatta, 2009; Wohl et al., 2013; Galia et al., 2016).

These morphologic changes affect channel hydraulics, since, upstream of check dams, water flows through larger cross sections (thus q increases), while, downstream, the stream is concentrated (lower q) in an incised thalweg. The changes in morphology and hydraulics of torrents determined by the presence of the check dams explain the significant inverse correlation between w/d and q and the direct correlation between q and LS shown by Pearson's matrix, detected in our study.

The adjustments of torrent morphology and hydraulic regime, induced by the check dams, influence also the surface and subsurface sediment size. These hydrological and geomorphic processes explain the significant correlations found by this study among hydrological and geomorphological indicators (w/d, LS and q) on one hand and sediment grain size characteristics (SD_{50} and SSF) resulting from the actions of check dams on torrent headwaters.

Many authors previously observed that the check dams, slowing down the water stream and inducing sedimentation of the finer material upstream of the check dam, interrupt the natural sediment transport; as a consequence, the under-saturated water flow increases its erosive capacity and induces bed scouring downstream (Conesa-García and García-Lorenzo 2010; Bombino et al. 2008; Conesa-García et al. 2007; Lenzi et al. 2003; Shieh et al., 2007). These processes comply with the results of our study, since, as explained above, upstream of check dams, water stream flows in enlarged cross sections (higher w/d) of channels with gentler slopes (lower LS) and reduced unit discharge (lower q); therefore water velocity is slower and part of the kinetic energy of the stream is reduced, which encourages sedimentation of finer particles (higher SSF) in the sediment wedge behind the wall. Since part of these sediments is trapped in the coarser fractions of channel bed, it results a lower caliber of surface sediments (lower SD_{50}). In the wider and flatter reaches upstream of each check dam, the depositional surface behind the wall is relatively stable when the storage capacity is filled (Liu, 1992), as in the case of the check dams surveyed in our study (Zema et al., 2014; Fortugno et al., 2017).

Conversely, downstream of check dams, the investigation evidenced that the water stream is more concentrated (higher q), but it is also more limpid, since it has lost much of the sediment load (deposited upstream, since over-saturated); thus, since its erosive power is increased, channel bed is scoured and narrowed (lower w/d) and its slope is steeper (higher LS). In these downstream sub-reaches, the erosion process mobilizes part of the bed material, which looses its finer fraction (lower SSF) and thus becomes coarser (higher SD_{50}). Findings of our study fit other literature experiences. For instance, in ephemeral streams of South-East Spain Boix-Fayos et al. (2007) found upstream of check dams very fine sediments ($SD_{50} < 1$ mm), while the SD_{50} downstream of most of the check dams was between 20 and 200 times coarser than upstream; occasionally very fine sediments (SD_{50}

< 2 mm) also appeared downstream of some check dams. Also in these ephemeral streams the coarsening probably resulted from a selective scour of fine sediments: owing to reduced transport capacity in sedimentary wedges, downstream sediment supply decreased (Galia et al., 2016). This alteration of sediment transport connectivity most likely caused the selective scouring of fine particles from the channel bed, which prevented the systematic downstream fining of the sediment calibres (Galia and Škarpich, 2016). Bed armouring may explain also the higher LS detected in the D reaches compared to both U and D transects. In fact, the higher sediment size prevents the "rotation" of the longitudinal profile between two consecutive check dams, due to scouring downstream and sedimentation in the upstream wedge after check dam installation. Moreover, bed armouring leads to a decrease in flow velocity due to the higher channel bed roughness; however, this effect can not compensate the increase of flow velocity due to the steeper longitudinal slope and channel narrowing.

Construction of a check dam not only changes bed slope and channel shape as well as flow regime, but also alters habitat form and structure, impacting river ecology (Winston et al., 1991; Franklin et al., 1995; Shieh et al., 2007). Land terracing and check dams stabilize hillslopes and slow down erosion, thus enabling ecological recovery, because of the increased probability of vegetation becoming established (Mongi-Manso et al., 2016).

In the studied headwaters, as it will be shown below, the characteristics of riparian plant communities may be affected according to the prevailing geomorphic processes (Steiger et al., 2005), and can be quantitatively linked to the morphological, hydraulic and sediment characteristics of the channel. However, in our study, in spite of the noticeable effects played on the physical parameters of the active channel, check dams have not altered significantly the characteristics of riparian vegetation upstream of the control structures, except for its transverse uniformity (lower CV_{GCC} and CV_{WCH}). In other words, it is true that higher cover and height of vegetation were found compared to less disturbed zones (as already demonstrated in other investigations, Bombino et al., 2008; 2009), but the most evident effect directly linked to the installation of check dams seemed to be water stream lamination, which reduced the hydraulic strength and thus made more uniform water stress on the vegetation across the transect, compared to the undisturbed zones: higher width to depth ratios, lower unit discharges and finer bed sediments - all significantly different between U and C zones - provided more favourable edaphic conditions and a lower disturbance across the transects, in which vegetation can develop with lower spatial variability (Bombino et al., 2009). Overall, upstream of check dams, finer sediment is retained, generating opportunities for vegetation to re-establish as a result of sediment retention and slope stabilization (Ramos-Diez et al., 2016b). Moreover, in the same environment as our study, these latter authors and Navarro et al. (2014) observed that higher vegetation cover stabilised substrate and reduced erosion processes to minimum values in both areas under study with respect to the bare land.

Conversely, in the transects located downstream of the check dams the extent and development of riparian vegetation is significantly lower with respect to control zones, which may be mainly explained by the significant effects measured in the studied headwaters, as: the extirpation phenomena exerted by the water stream (due to the higher q) and the removal of the sub-surface finer sediment (shown by the lower SSF due to the higher SD_{50}). This latter effect was also noticed by Bombino et al. (2008) in an investigation on one of the studied fiumaras (Sant'Agata torrent), and by Boix-Fayos et al. (2007), who in their study torrents of SE Spain observed a general pattern of armouring of the channel locally downstream of check dams.

In our study, the biodiversity of riparian vegetation seemed to be much less influenced than the other vegetal characteristics by the changes in torrent morphology, hydraulic regime and sediment characteristics due to the check dam presence. As a matter of fact, the extent of the surveyed changes were not of the same order of magnitude as the geomorphic and hydrologic adjustments recorded in the studied channels, in spite of the higher species richness and evenness observed upstream of check dams and, on the contrary, the parallel decrease detected downstream. Only the incidence of alien species on the native ones (that is, higher Ns_A/Ns_N upstream of the check dams and lower values of this parameter downstream) was found significantly different between D transects and the other headwater zones: this was ascribed by Bombino et al. (2014) to the terrestrial character that the riparian vegetation assumes in these local contexts, where some herbaceous species of the riparian environment (typical of the undisturbed transects) are lost at the early growth stage, due to the action of the erosive stream power (significantly higher q compared to C transects). As regards the similarity between groups of transects, AHC analysis revealed strong similarities between upstream and control sub-reaches; this was demonstrated by the fact that all U and C transects fall in the first cluster (C_1), which includes also six D transects (Figure 4); these latter transects are those characterised by the lowest values of PC_1, therefore showing physical and vegetal characteristics more similar to other transect groups. The remaining D transects fall in two other clusters (C_2 and C_3), but two transects of cluster C_3 (SAD1 and GD1) show extreme values of some indicators (namely SD_{50}, SSF, WCH, CV_{GCC} and Ns_A/Ns_N), which are discriminated from all the other transects (presumably because these transects belong to the first check dams of the staggered series of the two torrents).

6. CONCLUSIONS

The study has evaluated the physical (morphology, hydrology, sediment) and vegetation characteristics in transects around check dams (upstream and downstream) and far from the direct influence of the structures (control transects). Compared to these latter zones, 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). The actions of the control structures on torrent longitudinal slope and biodiversity of vegetation were less significant. The differences on bed profile slope were significant only between upstream and downstream transects. 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.

When the cover, structure and transverse variability of riparian vegetation were regressed on morphological, hydraulic and sedimentary variations of channel characteristics induced by check dams, high coefficients of correlations were found for the majority of the linear regressions. This means that direct, simple and quantitative linkages between torrent hydraulics, geomorphology and vegetation characteristics exist in the analysed headwaters; 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.

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TABLES

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	

[a] Estimated from 1:25000 scale maps

[b] Estimated from the relationships $T_m = 18.294 - 0.007A$ for the Ionian coast e $T_m = 16.913 - 0.006A$ fro the Thyrrenian coast, both developed using gauged data within the basins; where: T_m = Mean annual temperature in ^{o}C; A = Altitude in 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)

Table 2 – Physical and vegetation indicators adopted in this study together with their significance and survey/calculation methods.

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		Field survey/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)
		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/-

Table 3 – Statistical significance of differences (performed by Kruskal-Wallis test) in physical and vegetation indicators (measured in transects around 20 check dams) in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Parameter	**Transect group**		
	U/C	*D/C*	*U/D*
w/d	**	*	**
LS	*	*	**
q	**	**	**
SD_{50}	**	**	**
SSF	**	**	**
GCC	*	**	**
WCH	*	**	**
CV_{GCC}	**	*	**
CV_{WCH}	**	*	**
H_0	n.s.	n.s.	n.s.
H_2	n.s.	n.s.	n.s.
Ns_A/Ns_N	n.s.	**	**

Notes: U = upstream; D = downstream; C = control; ** = significant (at $p < 0.01$); * = significant (at $p < 0.05$); n.s. = not significant.

Table 4 – Pearson's correlation matrix between couples of physical and vegetation indicators (measured in transects around 20 check dams) in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Indicators			**Physical**					**Vegetation**						
			Morphology		*Hydraulic*	*Sediment*		*Development*				*Biodiversity*		
			w/d	*LS*	*q*	SD_{50}	*SSF*	*GCC*	*WCH*	CV_{GCC}	CV_{WCH}	H_0	H_2	Ns_A/Ns_N
Physical	*Morphology*	*w/d*	**1**											
		LS	-0.428	**1**										
	Hydraulic	*q*	-0.729	0.666	**1**									
	Sediment	SD_{50}	-0.518	0.526	0.775	**1**								
		SSF	0.836	-0.501	-0.776	-0.649	**1**							
Vegetation	*Development*	*GCC*	0.752	-0.674	-0.799	-0.607	0.814	**1**						
		WCH	0.796	-0.660	-0.780	-0.607	0.821	0.941	**1**					
		CV_{GCC}	-0.785	0.421	0.530	0.337	-0.632	-0.621	-0.652	**1**				
		CV_{WCH}	-0.858	0.542	0.784	0.573	-0.814	-0.748	-0.763	0.837	**1**			
	Biodiversity	H_0	0.295	-0.097	-0.342	-0.372	0.322	0.237	0.260	-0.204	-0.250	**1**		
		H_2	0.150	-0.175	-0.350	-0.389	0.251	0.213	0.161	-0.116	-0.200	0.795	**1**	
		Ns_A/Ns_N	0.403	-0.178	-0.578	-0.565	0.523	0.400	0.366	-0.215	-0.419	0.635	0.647	**1**

Note: acronyms of indicators are reported in Table 2; Pearson's coefficients are reported: in red, when they are not significant (at $p < 0.05$); in yellow, when higher than 0.50 and significant (at $p < 0.05$); in green, when higher than 0.75 and significant (at $p < 0.05$).

FIGURES

Figure 1 - The locations of the four study watersheds (“A” Allaro, “TG” Torbido di Gioiosa, “G” Gallico and “SA” Sant’Agata).

Figure 2 – Schematic cross section of a typical transect in the mountain reaches of the Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Figure 3 - Box and Whisker plots for physical and vegetation indicators measured at upstream (U), downstream (D) and control (C) transects around 20 check dams in the mountain reaches of the Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Note: Different letters indicate significant differences among groups of transects (at $p < 0.05$ of Kruskal-Wallis test)

Figure 4 - Dendrogram provided by Agglomerative Hierarchical Cluster (AHC) analysis applied to the physical and vegetation indicators measured in upstream (U), downstream (D) and control (C) transects around 20 check dams in the mountain reaches of Allaro (A), Torbido di Gioiosa (TG), Gallico (G) and Sant'Agata (SA) torrents (Calabria, Southern Italy).

Figure 5 - Scheme of the channel and vegetation dynamics of Mediterranean semi-arid headwaters under natural conditions (a) and after check dam installation (b).

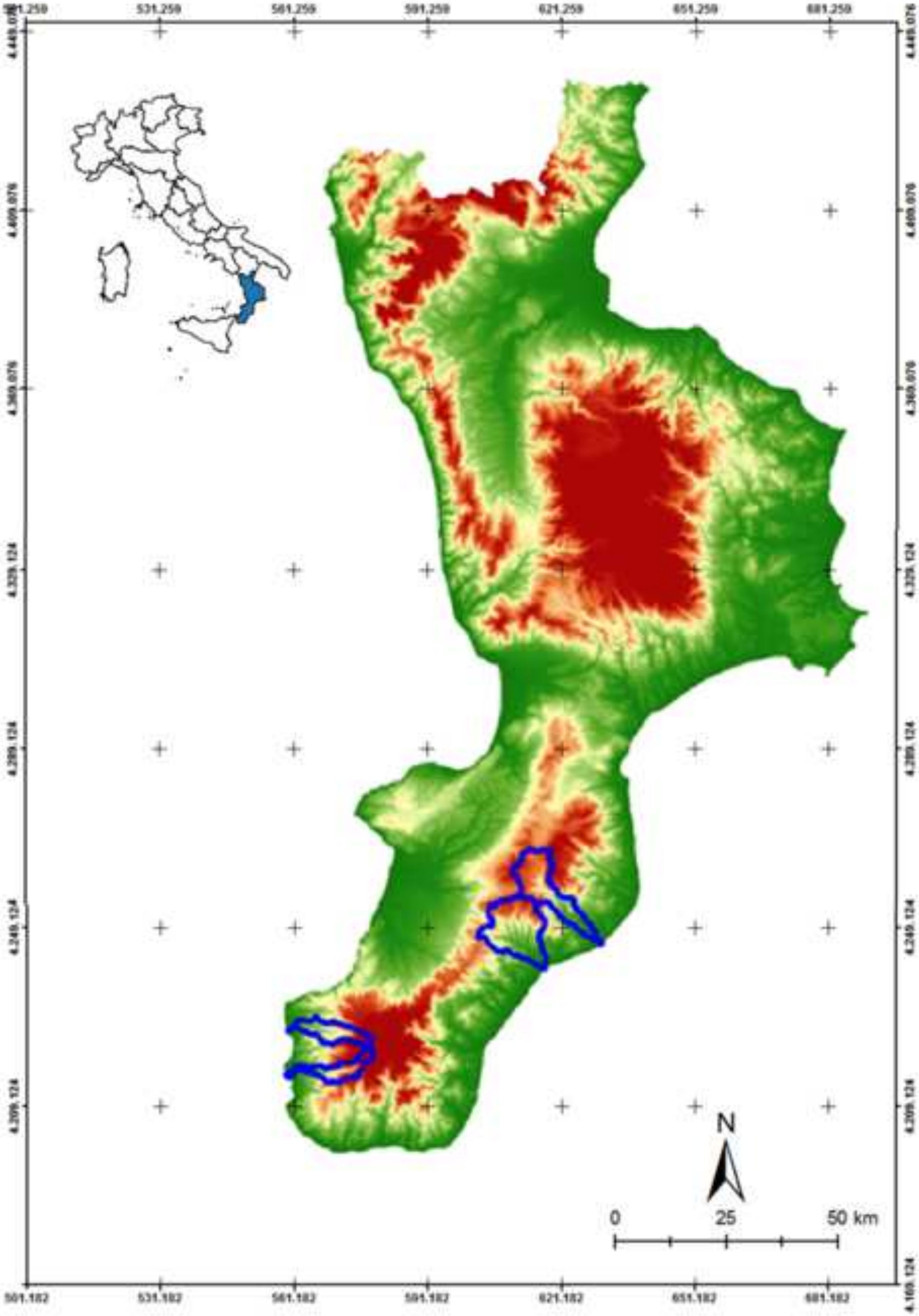
Legend

w/d: width/depth ratio; q specific discharge; LS: channel longitudinal slope; SD_{50}: surface sediment median diameter; SSF: finer sub-surface sediment content; GCC: Global Canopy Cover; WCH: Weighted Canopy Height; CV_{GCC}, CV_{WCH}: Coefficients of Variation of GCC and WCH; H_0: α-diversity ($\alpha = 0$); H_2: α-diversity ($\alpha = 2$); Ns_A/Ns_N: ratio alien/native species; T = return interval of floods (years).

a) The mountain streams of the Mediterranean semi-arid environment are high-energy and hazardous hydro-systems, characterized by small basins with torrential regime and steep slopes. Frequent and intense rainstorms produce high-magnitude flash floods with high erosive power, often causing hydro-geological instability and destruction of human works. Under natural conditions the active channel shape and profile, the bed sediment caliber and distribution as well as the spatial connectivity of structure, habitat, evolution and biodiversity of vegetation are dominated by a state of non-equilibrium associated with fluvial processes and landform dynamics. These features can be measured in transects of the active channel by a set of significant indicators: channel shape (w/d) and longitudinal slope (LS); water flow unit discharge (q); surface sediment size (SD_{50}) and finer sub-surface sediment content (SSF); vegetation extent (GCC) and development (WCH); vegetation transverse variability (CV_{GCC}, CV_{WCH}); vegetation species richness and relative abundance (H_0 and H_2), and degree of vegetation integrity (Ns_A/Ns_N), in order to quantitatively evaluate and understand the channel and vegetation dynamics.

b) In mountain reaches, where natural disturbance plays an important role to maintain discontinuity and diversity of riparian zones, the interaction between hydrological, geomorphological, and ecological processes can be strongly affected by check dams, widely built by local administrations to control and mitigate the hydrological risk over the last 70-80 years. The check dams significantly alter ecohydrological and geomorphological dynamics and these changes are evident in transects located immediately upstream and downstream of the check dams compared to the intermediate zone between two check dams (that can be considered as 'control', because they are representative of zones not locally disturbed by check dam and thus reflecting the conditions of the active channel before construction).

Figure 1


501.259
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561.259
591.259
621.259
651.259
681.259
4.449.076
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4.369.076
4.329.124
4.289.124
4.249.124
4.209.124
4.169.124
N
0
25
50 km
501.182
531.182
561.182
591.182
621.182
651.182
681.182

Figure 2


Riparian habitat
Terrestrial habitat
Terrestrial habitat
Ecotonal habitat
Ecotonal habitat

Figure 3a

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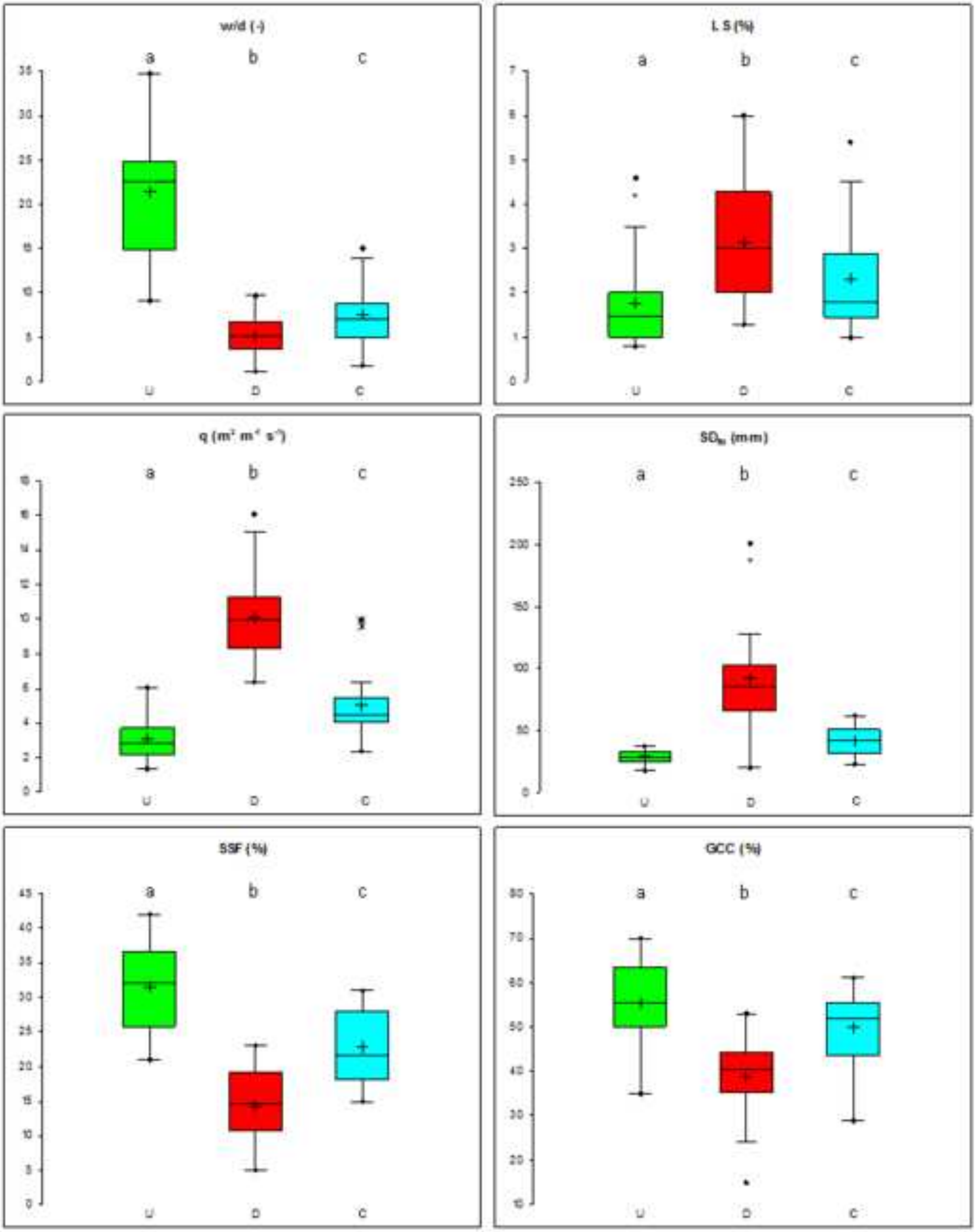

Figure 3b

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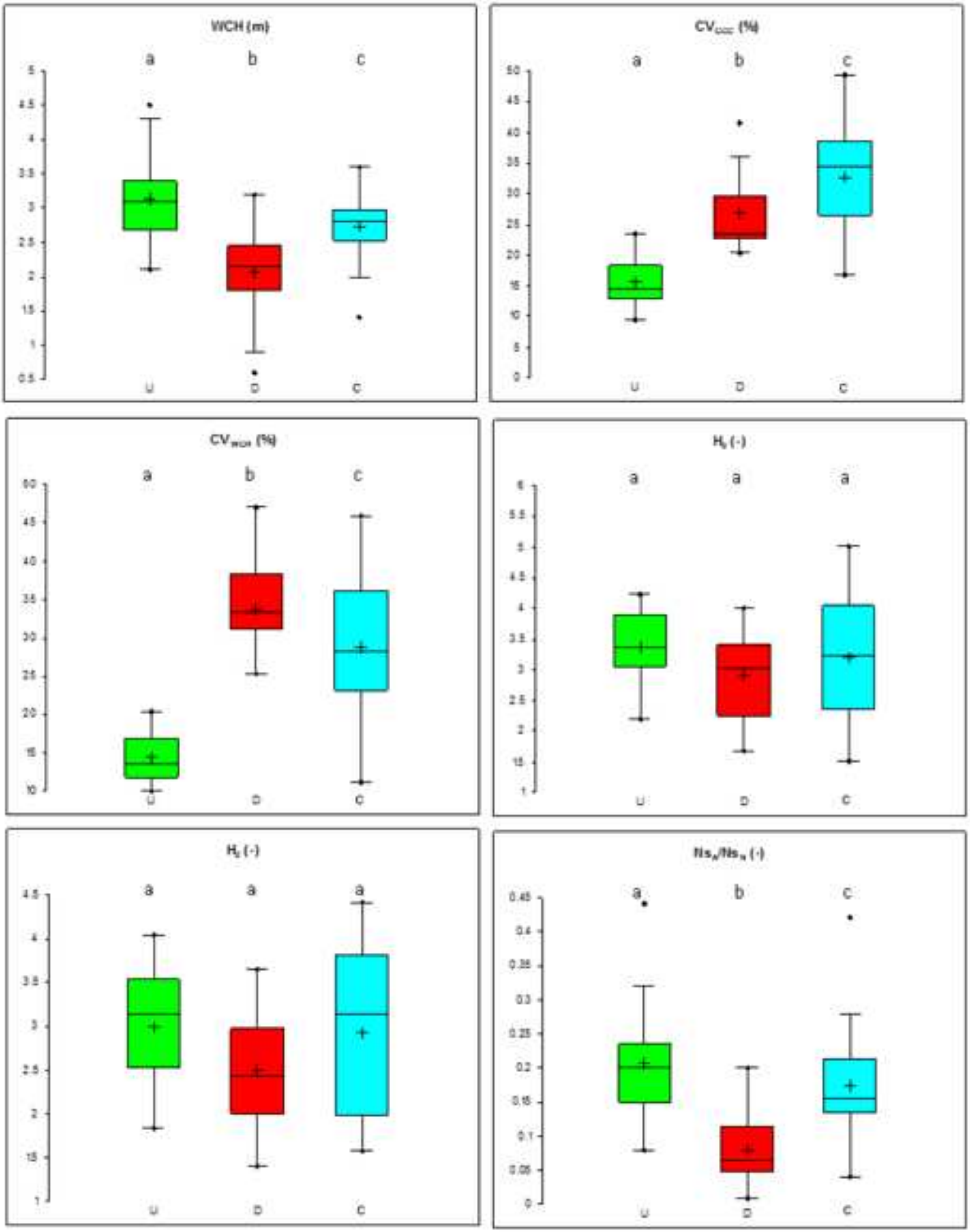
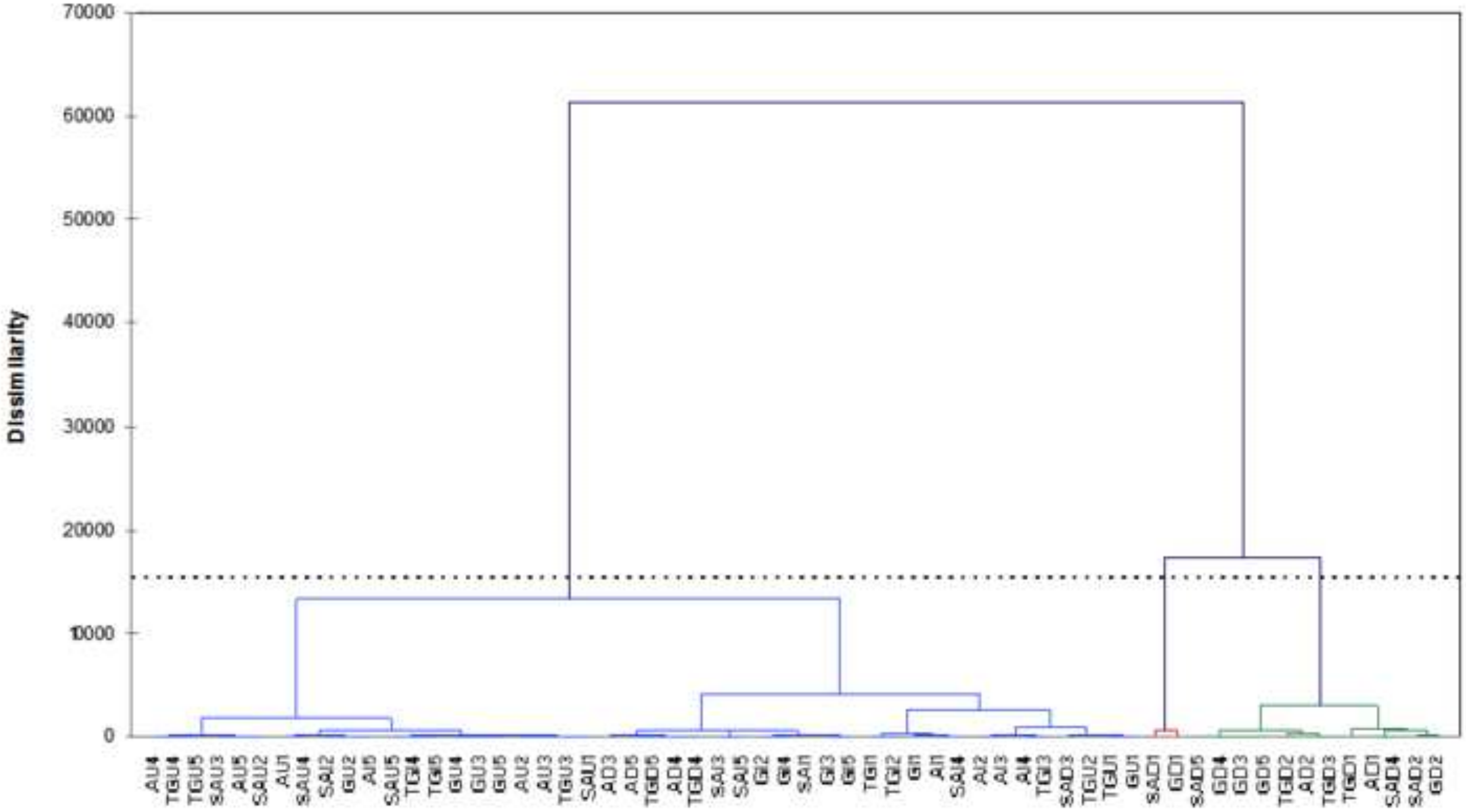


Figure 4


Dissimilarity
70000
60000
50000
40000
30000
20000
10000
0
AU4
TGU4
TGU5
SAU3
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SAU2
AU1
SAU4
SAI2
GU2
AI5
SAU5
TGI4
TGI5
GU4
GU3
GU5
AU2
AU3
TGU3
SAU1
AD3
AD5
TGD5
AD4
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SAI3
SAI5
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GU1
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GD1
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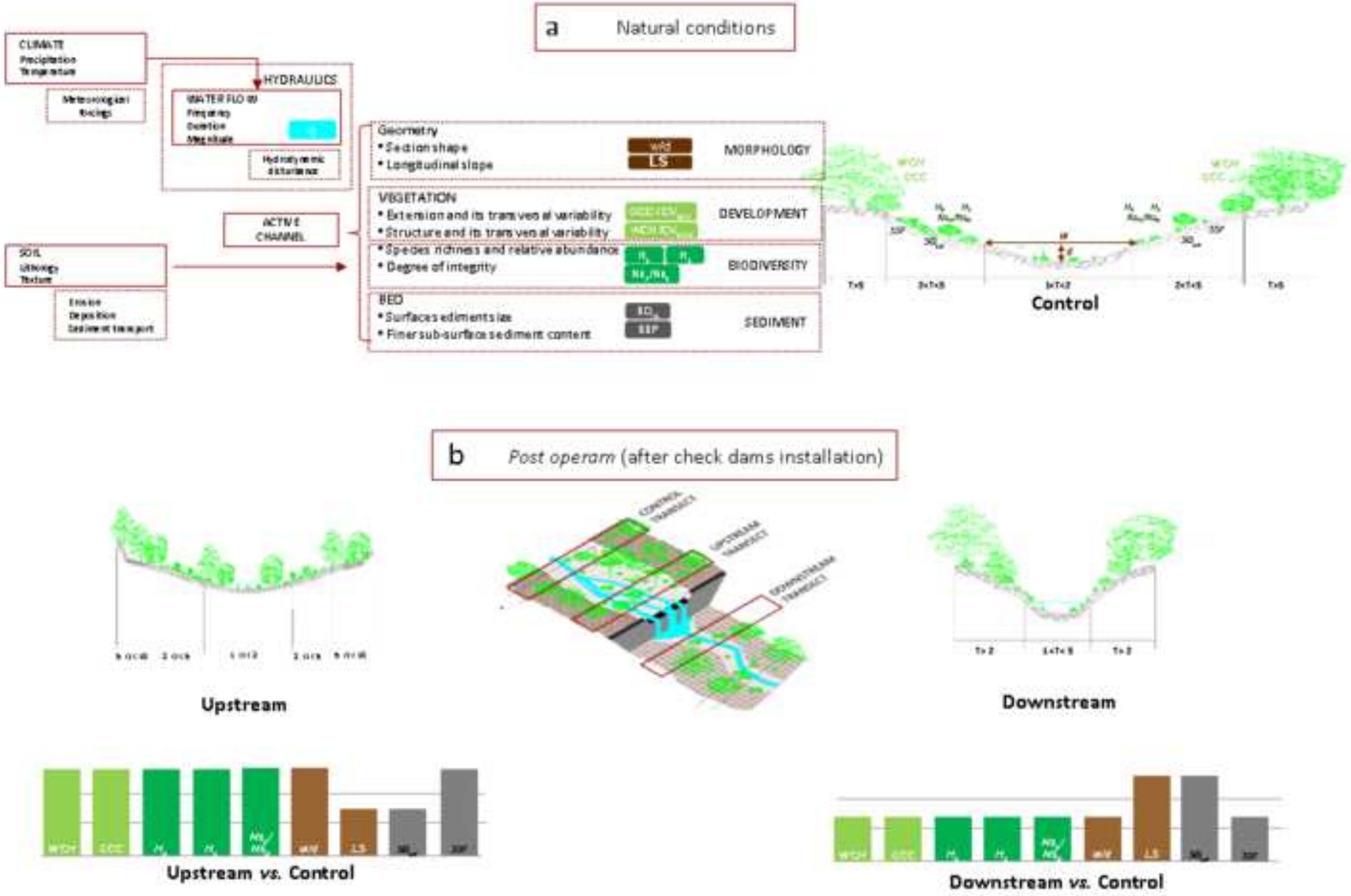
TGD3
TGD1
AD1
SAD4
SAD2
GD2

Figure 5


a
Natural conditions
CLIMATE
Precipitation
Temperature
Meteorological forcings
HYDRAULICS
WATER FLOW
Frequency
Duration
Magnitude
Hydrodynamic disturbance
ACTIVE CHANNEL
SOIL
Lithology
Texture
Erosion
Deposition
Sediment transport
Geometry
• Section shape
• Longitudinal slope
w/d
LS
MORPHOLOGY
VEGETATION
• Extension and its transversal variability
• Structure and its transversal variability
DCC (CV)
WCH (CV)
DEVELOPMENT
• Species richness and relative abundance
• Degree of integrity
H
H
Nk/Nk
BIODIVERSITY
BED
• Surface sediment size
• Finer sub-surface sediment content
SD
SSP
SEDIMENT
WCH
DCC
SSP
SD
w
d
T>5
2<T<5
1<T<2
Control
b
Post operam (after check dams installation)
CONTROL TRANSECT
UPSTREAM TRANSECT
DOWNSTREAM TRANSECT
Upstream
Downstream
T>2
1<T<5
WCH
DCC
H
H
Nk/Nk
w/d
LS
SD
SSP
Upstream vs. Control
Downstream vs. Control