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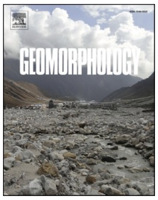

Relationships between torrent check dam systems and shoreline dynamics in semi-arid Mediterranean area: A sub-regional focus in Calabria, Italy

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ABSTRACT

The work reports the results of investigations on the historical evolution of the shoreline in relation to the presence of check dam systems along streams of the Mediterranean environment. To this end, a survey methodology specifically developed in a previous work, which provided initial indications worthy of more extensive evaluation, was integrated and applied to the watershed-coast system of eight Calabrian streams, six falling on the Ionian side and two on the Tyrrhenian side of the Aspromonte Massif, as the sides present significantly different climatic and geomorphological characteristics. The streams under investigation, with watershed areas ranging from 39.2 to 160.3 km^2, have been affected by relevant restoration programmes with transverse control works carried out over four periods from 1954 to today. Overall, about 690 check dams were examined, distributed over the "mountain", "intermediate" and "valley" reaches that were normalised for comparison purposes. Based on the intensity of intervention with check dams, five watersheds are included in the "medium-high" category and three in the "low" category. The volumes of sediment corresponding to shoreline movements (retreats or, less frequently, advances) and those retained upstream of the check dams, generally silted a few years after construction, were estimated and analysed. The overall results obtained highlight a relationship between the retirement tendency of the shoreline (with observed retreats up to 170 m and affected long shores up to 5 km) and the construction of transverse control works, suggesting that particular attention should be paid to the insertion of transverse works, as well as to their typology, in the valley reaches, in one effort to combine the requirements concerning with the hydrogeological safety and the stability of the shoreline asset, limiting the need of remediation measures for coastal protection, as it actually happens along the widespread urbanized strips.

1. Introduction

Since the second half of the 20th century, the monitoring of the shoreline evolution in the context of coastal erosion processes has become of increasing interest, especially in the Mediterranean area, and particularly in Italy, where a wide programme of river control works has been implemented over the decades (Aiello et al., 2013; Boix-Fayos et al., 2007; Coltori, 1997; Rosskopf et al., 2018). The shoreline dynamics finds one main driver in the flux of terrestrial sediments towards the watershed mouth (Anthony et al., 2014; Falqués, 2006; Leeder, 1999; Limber et al., 2008; Malara et al., 2020; Warrick, 2020; Willis and Griggs, 2003). The sediment delivery process depends on many inland factors (direct and indirect), both natural (e.g., climatic, morphogenetic and geodynamic, geo-lithologic and geomorphologic, vegetational) and anthropogenic (e.g. land use changes and hydraulic engineering works) (Comiti, 2012; Dunne et al., 2003; Gomez et al., 2003; Liébault et al., 2005; Montgomery and Buffington, 1997; Nakamura et al., 2000; Phillips et al., 2013). The shoreline dynamics is also dependent on several factors acting within the marine environment, such as the sea level rise due to climate change, storm surges (Dean, 2002; Leeder, 1999; Tsimplis et al., 2005; Tsimplis and Baker, 2000; Velegrakis et al., 2008; Vousdoukas et al., 2016) and the human interventions addressed to shoreline recovery and protection (Dixon, 1996; Poulos et al., 2000; Stanley and Warne, 1998).

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Changes can be short, intermediate, and long term. The short-term ones are mainly related to waves and currents; the intermediate-term ones, instead, are mainly related to anthropic action such as the construction of coastal and fluvial protection structures (Del Río and Gracia, 2013); while the long-term changes are mainly related to tectonic activity, subsidence, and sea level rise.

Especially in recent years the influence of torrent check dams on sediment connectivity within the so-called watershed-coast *continuum* (Malara et al., 2020) is widely debated by the scientific community (Bischetti et al., 2014; Boix-Fayos et al., 2007; Castillo et al., 2007; Combes, 1989; Conesa-García et al., 2007; Conesa-García and García-Lorenzo, 2009; deWolfe et al., 2008; Fesquet, 1997; Hall, 2005; Nichols et al., 2016; Quiñonero-Rubio et al., 2016). The local sediment storage and the reduced sediment transport capacity of the stream flow, due to the implementation of transverse hydraulic structures, have been recognized among the possible causes of shoreline retreat around the world (Acciarri et al., 2016; Aiello et al., 2013; Batalla, 2003; Boix-Fayos et al., 2007; Coltori, 1997; Kondolf, 1997; Kuleli, 2010; Martínez Del Pozo and Anfuso, 2008; Miao et al., 2010; Rosskopf et al., 2018; Wang et al., 2012; Wohl et al., 2015; Xu, 2005; Zhao et al., 2017). On the other hand, torrent control measures, such as check dams or similar structures, are required to cope with hydrogeological risk within the watershed; their implementation, without realistic alternative solution in most cases, is a crucial safety factor especially in the mountain areas, usually characterized by hydrological regimes and geomorphological assets that increase the exposure of the watershed to vulnerability and disorder. Sediment connectivity within the watershed-coast *continuum* is thus a complex issue requiring an integrated systemic approach in an effort to "balance" the contrasting factors and expectations in a sustainable and tendentially balanced way.

The Calabria region (southern Italy), with its 750 km of coastline, can represent a significant case study in the Euro-Mediterranean area, both for the widespread phenomena of shoreline retreat and the considerable number of check dam systems for the control of torrents built mainly in the early second half of the last century (Antronico et al., 1998; Bombino et al., 2021, 2022b; Petrucci and Polemio, 2007). Indeed, following devastating events (Sabato and Tropeano, 2004; Sorriso-Valvo et al., 1995), at the beginning of the 1950s, the Italian government issued Special Laws concerning the Calabria region and allocated huge funds for the construction of protective works to mitigate hydrogeological instability and reclaim marshy areas (Acerbo, 1937; Bevilacqua, 1987; Medici, 1954; Petrucci and Polemio, 2007; Ruini, 1913). About 150,000 ha have been reforested, hundreds of kilometres of embankments and around 10,000 check dams (weirs) were implemented (A.FO.R., 1998; Bombino et al., 2022b; D'Ippolito et al., 2013; Petrucci and Polemio, 2007). From 1950s to 1990s >8 billion euros were invested (Bombino et al., 2022a), of which approximately 35 % in the headwaters and mountain stream reaches, 20 % in the intermediate reaches and 45 % in the valley reaches. Furthermore, some 210 million euros have been invested in coastal protection works since the 2000s.

A considerable number of watersheds have been intensively structured with several thousand check dams from upstream to downstream, especially in the area of the Strait of Messina (in southern Calabria). Approximately 2/3 of check dams is distributed below 350 m a.s.l. (PAI Calabria - Hydrogeological Asset Plan, 2001 - https://www.distrettoappenninomeridionale.it/index.php/elaborati-di-piano-menu/ex-adb-calabria-menu/piano-stralcio-assetto-idrogeologico-rischio-idraulico-menu).

Recently, some Authors have investigated the evolution of the shoreline near the mouth of some Calabrian torrents (Barbaro et al., 2019; Foti et al., 2019, 2022a, 2022c). The raising of the riverbed due to the immobilization of large amounts of sediments (with consequent increase in overflow risk) has been observed in other studies (Bombino et al., 2022b; Sabato and Tropeano, 2004). A study focus concerns the fiumara Gallico (Aspromonte Massif system in southern Calabria) that flows right down to the Strait of Messina (Bombino et al., 2022a). The Gallico watershed has been subject to an intensive programme of hydraulic river regulation since the 1950–60's: 264 check dams (2/3 of which installed a few kilometres from the coast), completely filled a few years after their construction, have been analysed in order to explore the relationships between the sediment volumes retained by the transverse hydraulic structures and the shoreline changes over time. In particular, according to a methodology purposely developed to analyse the effect of sediment trapping within three sub-reaches (mountain, intermediate and valley), the limiting influence on the shoreline evolution has been documented, highlighting the need to pay particular attention to the hydraulic control methods of valley reaches, looking for further and more extensive data on the detected effects.

Based on the results of study conducted on the *fiumara* Gallico, the present work aims to verify the recurrence and representativeness of relationships between the check dam systems and the shoreline dynamics, under the different conditions (both climatic/physiographic and in terms of intensity of intervention) of the two opposite Tyrrhenian and Ionian sides of the Aspromonte Massif system covering the south of the Calabria region, Italy.

2. General overview of the Aspromonte Massif system and its Tyrrhenian and Ionian sides

2.1. Climatic and hydromorphological characteristics

The Aspromonte Massif system is located in southern Calabria, the tip of the Italian "boot", with Sicily to the south-east. The Massif lies in one of the most geo-dynamically active sectors in the central Mediterranean area, where crustal deformation is ongoing as a result of the Africa-Europe collision (Billi et al., 2007). The landscape and morphology of the entire mountainous complex is strongly controlled by geo-lithology and structure as well as by the intense uplift that occurred during the Quaternary (Robustelli, 2019; Sorriso-Valvo and Sylvester, 1993). Aspromonte rises to an average elevation of approximately 1100 m a.s.l. A numerous series of peaks (higher than 1400 m) creates an intricate and rugged mountain system, shaped like a pyramid with the top of "Montalto" (1956 m) at its centre and at a distance of only 20–30 km from the Tyrrhenian and Ionian Sea (Fig. 1). The core of the Massif and much of the western part is composed by Palaeozoic metamorphic (slate, phyllite, schist and gneiss) intruded by granitoids. Three tectono-metamorphic units are usually recognized (Cirrincione et al., 2008), strongly affected by slope instability because of the high degree jointing and differentiating the two opposite sides, on which a multitude of watercourses drain to the Tyrrhenian and Ionian coasts (Sorriso-Valvo and Sylvester, 1993). The Ionian side slopes more gently towards the sea (Robustelli, 2019).

Overall, the climate varies from Mediterranean humid or sub-humid on upper mountain reliefs (with modifications characterized by wetter/cool summer and colder winters, and snow cover for >3 months above 1600 m a.s.l.) to Mediterranean semi-arid (with mild winters and hot dry summers) over the coast strip (Le Pera and Sorriso-Valvo, 2000). Precipitation (on average 1100 mm y^{-1}) ranges from 450 to 2000 mm yr^{-1} (Bellecci et al., 2002; Coscarelli and Caloiero, 2012) and is strongly dependent on orography; it is concentrated in the autumn-winter period and varies from about 2200 mm per year recorded at the Polsi station (786 m a.s.l.) to just over 500 mm in the Ionian coastal zone (Capo dell'Armi), where the hottest and driest areas in Italy reside, with average temperature of about 19 °C and average annual precipitation not exceeding 450 mm. Average annual temperatures range from 19 °C in coastal areas to 10 °C in mountainous areas.

The Aspromonte Massif system is an Apennine ridge perpendicular to the main wet currents. In relation to its geographic position and mountain nature (a real orographic barrier in the middle of the Mediterranean Sea, between Europe and Africa), the Massif records a high climatic variability, while the opposite slopes (Tyrrhenian and Ionian) fall under different climatic sub-zones (Critelli et al., 2011; Versace

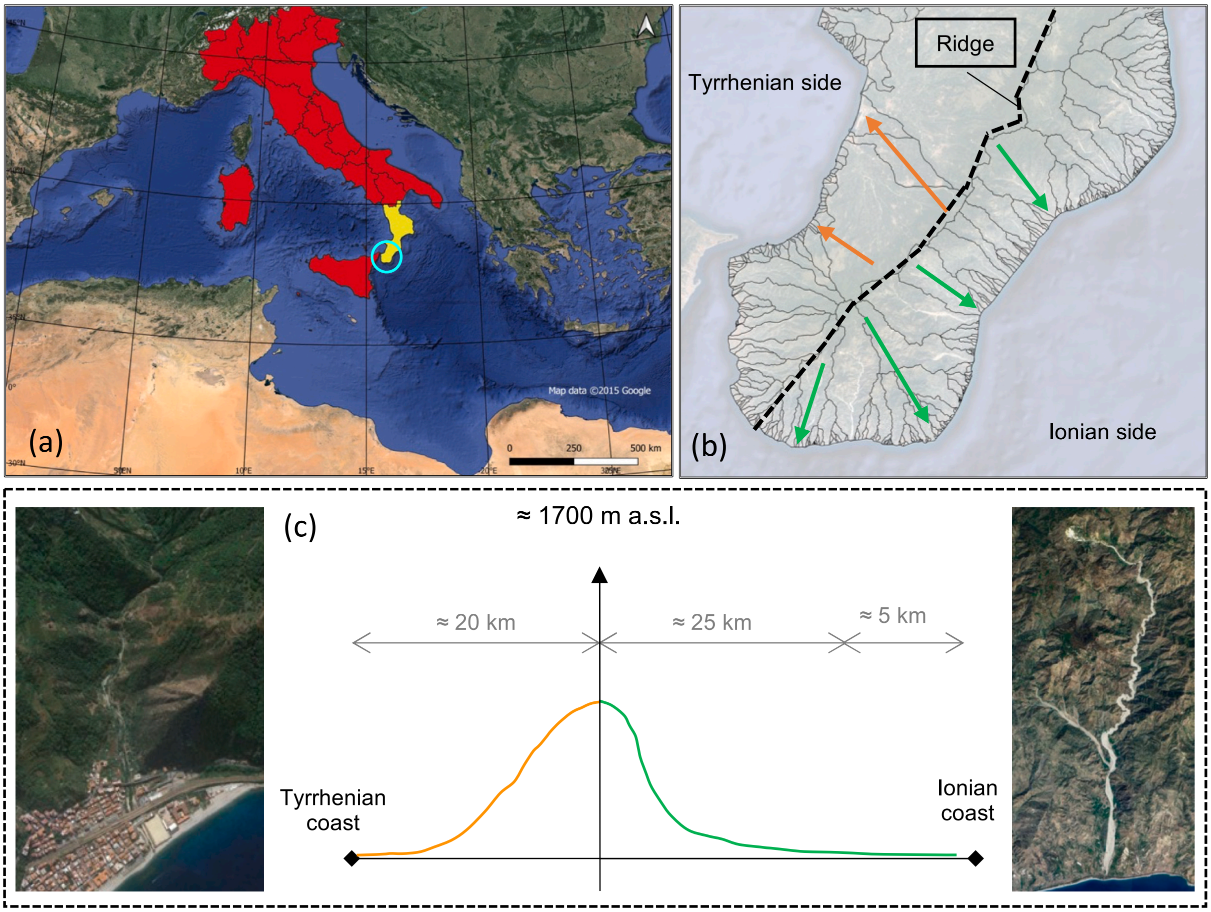


Fig. 1. (a) Geographic setting of the Calabria region; (b) and (c) sketches of the extent and elevation profile of the two opposite slopes (Tyrrhenian and Ionian) of the Aspromonte massif system, southern Calabria.

et al., 1989) showing significant differences. The Tyrrhenian side, facing north-west, subject to western currents with lower temperatures and very frequent orographic-type rainfall (Caloiero et al., 1990; Versace et al., 1989), is on average cooler and rainier, with average temperatures about 2 °C lower and precipitation about 35 % higher, distributed over two or more rainy days (Terranova and Iaquinta, 2011). The Ionian side (south-east) is warmer and, although less rainy, is more affected by extreme events (meteorological disturbances mainly generated from Africa), that can reach 170 mm h^{-1}. Consequently, natural landscapes (relief shapes, biodiversity, vegetation aspects) of the two sides are also affected by these differences.

The extent of the Tyrrhenian side, where the landscape is highly influenced by the tectonic activity (Robustelli, 2019), is lesser than the Ionian one (Sorriso-Valvo and Terranova, 2006). The first one present series of narrow elongated marine terraces (detectable at 100–200 m, 350 m and about 590 m a.s.l.) running parallel to the coastline. The flanks of the Ionian side generally decrease more regularly and hillslopes along the main rivers and in the tributary valleys are very steep (Robustelli, 2019).

Generally, the watersheds on both sides have steep and rugged slopes and widespread mass movements: extreme events mobilise a large amount of mass and river debris as a result of pulsive/aggressive climate. Streams originated at the edge of Aspromonte Massif (Palaeozoic metamorphic relief) go through alluvial deposition plains and reach the sea with short and steep beds (Petrucci and Pasqua, 2012). The degradational zone has gravel beds quite wide and dry during most of the year (Marchetti, 2000). The drainage network consists mainly of torrents - the so-called "fiumara" (Bombino, 2020) - with short channels (around 10–20 km) and relatively small watershed (in most cases less than a 100 km^2; Sabato and Tropeano, 2004; Sorriso-Valvo and Terranova, 2006).

In their upper reaches most streams are steep bedrock rivers (Robustelli, 2019). The "fiumare" that outflow into the Tyrrhenian Sea are short (with length < 20 km) and extremely steep, flowing in a straight line and are approximately perpendicular to the coastline; in the narrow coastal plain, which is densely urbanized, steep cliffs delimit outcrops of narrow and discontinuous deposits (alluvial/colluvial and marine) (Fig. 1). Close to the Ionian coast, the fiumare show disproportionately wide riverbeds (reaching a 1 km in width) as if to accommodate inundations by floods of several hundred cubic meters; actually, the water flows, when present during the year, usually occupy a rather small portion of the riverbed, with rare exceptions concerning flow return periods of tens of years (Fig. 1) (Caloiero et al., 2019; Ferraro et al., 2017; Foti et al., 2022a, 2022b).

3. Methodology

According to the aim of the work, the following methodologic steps were undertaken: (i) selection of watershed-coast case studies in the two opposite sides of the Aspromonte Massif system; (ii) characterisation of coastal processes and (iii) of land use; (iv) classification of watershed-coast case-studies according to the "intensity of intervention" with check dams; (v) stream subdivision into mountain, intermediate and valley reaches; (vi) evaluation of sediment volumes retained by the check dam systems within stream reaches; (vii) evaluation of the shoreline changes; (viii) cross analysis of the results either at watershed level or between watersheds-coast systems.

3.1. Selection of watershed-coast case studies

The available geo-database, which was developed through several extensive investigations (80 field surveys for a total of approximately 960 h and 24,000 km travelled; A.FO.R., 1998), was used to select the watershed-coast case studies. The following eight case studies, including the *fiumara* Gallico already investigated by Bombino et al. (2022a), were selected with the aim of including watershed with (i) the same order of magnitude in terms of area, (ii) the tendency of absence of both artificial embankments and coastal protection works in proximity to the watershed mouths, (iii) a variable (zero is not available) "intensity of intervention" with check dams (weirs) in the mainstream: Gallico (henceforth GA) and Sant'Agata (SA), in the Tyrrhenian side; Allaro (AL), Amusa (AM), Torbido di Gioiosa (TG), Bonamico (BO), Careri (CA) and La Verde (LV), in the Ionian side (Fig. 2). Given the difficulties in assembling the sample, two couples of adjacent watershed-coast systems (AL-AM and BO-CA, Fig. 2) with similar level of "intensity of intervention" with check dams were not discarded by looking at a paired analysis, in order to cope with the overlapping effects on the shoreline evolution. The main climatic and physiographic characteristics of the selected watersheds are reported in Table 1; those of mainstream check dam systems are shown in Table 2.

Since the beginning of the last century, before the implementation of the intervention campaigns, the valley reaches of the GA and SA fiumare were affected by canalisation, mainly built to protect the surrounding farmland. Initially, the embankments slightly narrowed the sections of the stream; later, as specified below, in the case of SA, the narrowing became drastic and resulted in a reduction in width of up to 2 orders of magnitude.

3.1.1. Coastal processes

Wave conditions between the two coasts are strongly differentiated. The Ionian Sea has a maximum depth >5000 m and a nearshore slope <2 %; it is characterized by considerable spatial variability of maritime features and intense waves can come from different directions varying between NE and SE. The Tyrrhenian Sea has a maximum depth of <4000 m and a nearshore slope varying from 2 % to 5 %; here, the intense wave conditions are more homogeneous and concentrated along a few directions (mainly NW), and there are no secondary and tertiary sectors; these conditions usually become aggressive in autumn and winter (Caloiero et al., 2019; Ferraro et al., 2017; Foti et al., 2022a, 2022b). The narrow area of the Strait of Messina, at the southern Tyrrhenian coast of Calabria, has very high nearshore slopes, often >10 %. In the Ionian Sea, instead, there is considerable spatial variability and the intense wave conditions can come from different directions, varying between N-E and S-E, and secondary and tertiary sectors are present in several locations.

Table 3 illustrates the main parameters of wave motion (maximum and average wave height, variation of wave height according to return period, direction, and energy of the flow) and sediment (mobilisation and qualitative characteristics of grain-size), which are responsible for regulating coastal dynamics and processes at the mouths of the studied streams. The comparison of the data shows a clear distinction between the basins on the Ionian side (AL, AM, TG, BO, CA and LA) of the Aspromonte Massif compared to those (SA and GA) on the Tyrrhenian side. A statistical difference ($p < 0.05$) was found between the two opposite sides, while there is no statistical difference ($p < 0.05$) between the values collected at the mouth-coast systems within the same side. The comparison, therefore, shows that the coastal processes within the Ionian side act consistently both in the watersheds intensively stabilised with check dams (AL, AM and TG) and in those without transverse control works (CA, BO and LV). No beach nourishment has ever been carried out at the mouth of the basins studied.

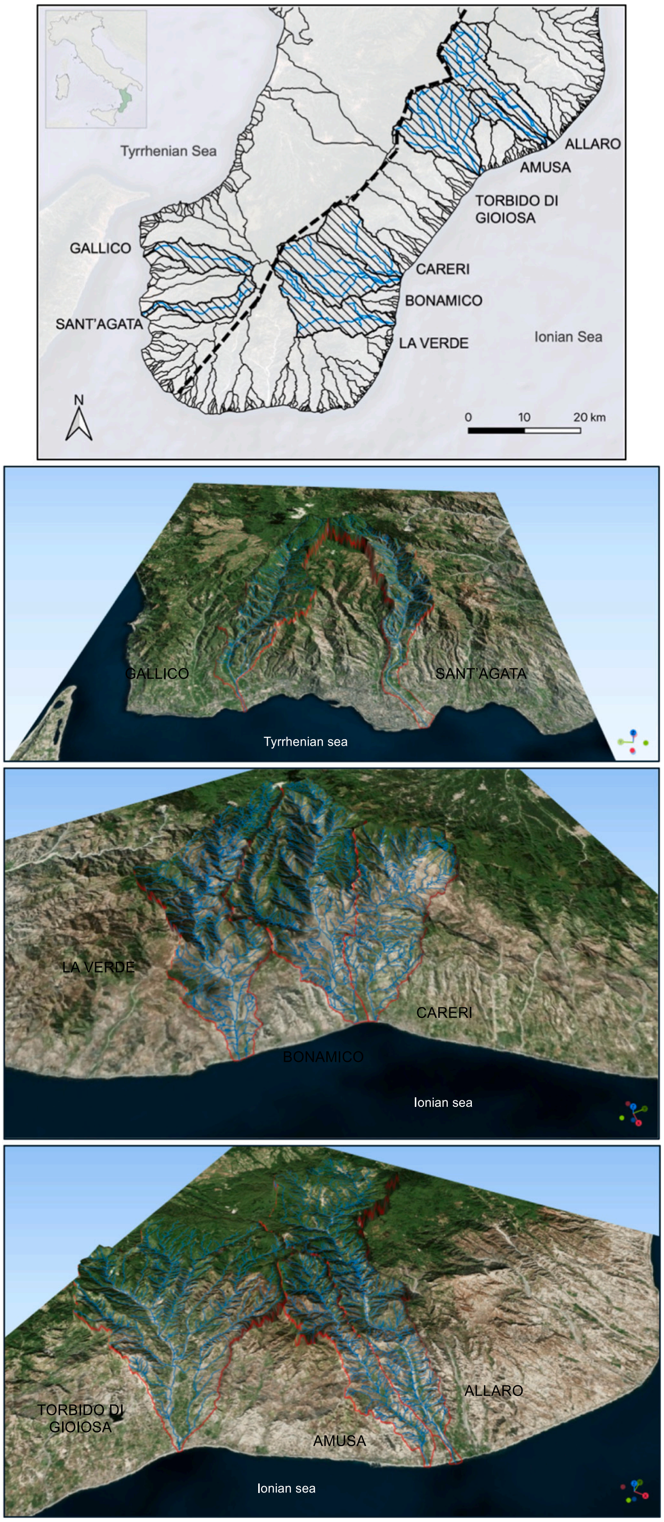


Fig. 2. Watershed-coast selected as case studies in southern Calabria, Italy.

3.1.2. Land-use

Land-use change in the studied watersheds was monitored in 1955 and in 2020. In 1955, the prevalent land-use in the eight case studies consisted of forest (up to 45 % of the catchment area, with natural stands of beech and fir), shrubland (on average about 10 %), agricultural areas (15 %, mainly arable land), natural grasslands (15 %) and residual non-vegetated areas. It is useful to reiterate that the mountainous part of the studied catchments has the same watershed, consisting of the Aspromonte Massif peak (whose conformation is similar to a pyramid) where dense forest prevails.

Table 1
Main climatic and physiographic features of the watersheds selected within the Tyrrhenian and Ionian sides of the Aspromonte Massif in Southern Calabria, Italy.

	Watershed							
	Tyrrhenian side		*Ionian side*					
	GA	**SA**	**AL**	**AM**	**TG**	**BO**	**CA**	**LV**
Climatic/Environmental conditions (a)	Csa	Csa	Csb	Csb	Csb	Csb	Csb	Csb
Meteo-station altitude (b) (m a.s.l.)	1187	1124	920	1084	704	786		1187
Mean annual rainfall depth (b) (mm)	1605	1310	1767	1818	1927	1760		1605
Mean annual air temperature (b) (°C)	10.7	11.3	11.5	11.9	13.9	14.5		10.7
Watershed area (km^2)	59.1	53.8	130.3	39.2	160.3	136.4	91.7	117.1
			169.6			228.1		
Maximum altitude (m a.s.l.)	1788	1665	1407	1200	1210	1925	1526	1919
Mean altitude (m a.s.l.)	707	857	732	469	582	778	404	749
Mean slope (%)	26.0	37.4	31.3	37.0	35.0	45.5	28.1	38.7
Horton-Strahler stream order (b)	V	V	VI	V	VI	VI	VI	VI
Mainstream length(b) (km)	21.0	23.6	17.4	12.3	20.3	31.0	20.5	36.5
			29.7			51.5		
Stream network length(b) (km)	258.9	280.0	634.1	214.9	791.0	693.6	446.0	599.4
Hypsometric integral (%)	40	47	52	38	48	40	26	39
Watershed shape factor	0.13	0.09	0.43	0.26	0.39	0.14	0.22	0.09
Drainage density (km^{-1})	4.38	5.22	4.86	5.48	4.93	5.09	4.86	5.12

Notes: GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; (a) Köppen classification (Kottek et al., 2006): "Csa" = hot Mediterranean climate and semiarid conditions; "Csb" = warm Mediterranean climate and humid conditions; (b) Data source: ARPACAL (www.arpacal.it) – until 2022; PAI Calabria - Hydrogeological Asset Plan, 2021 (https://www.distrettoappenninomeridionale.it/index.php/elaborati-di-piano-menu/ex-adb-calabria-menu/piano-stralcio-assetto-idrogeologico-rischio-idraulico-menu); for AL and AM as well as BO and CA, cumulative data are also presented in view of their coupled treatment (grey cells).

Table 2
Intensity of interventions with check dam (weir) systems in the watersheds case studies (from 1950s to 1990s, mainly through two watershed-scale intervention campaigns).

	Watershed							
	Tyrrhenian side		*Ionian side*					
	GA	**SA**	**AL**	**AM**	**TG**	**BO**	**CA**	**LV**
Number of check dams installed during the intervention campaigns								
1954–70s	196	97	35	29	143	3	3	2
70s–80s	53	26	10	9	39	–	3	–
80s–1996	11	5**	2	2	8	–	–	–
1996–today	4*	2	1	1	3	–	–	–
Whole period	264	130	48	41	192	3	6	2
			89			9		
Height of check dams								
Average value (m)	1.9	2.1	1.7	2.0	2.2	0.9	1.3	2.9
Range of variation (m)	0.9 ÷ 3.3	0.9 ÷ 3.7	0.8 ÷ 2.9	0.9 ÷ 3.4	1.0 ÷ 3.8	0.9	1.1 ÷ 1.5	2.9

Notes: GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; * construction of rock breakwater barriers; ** drastic narrowing, rectification and cementing of the riverbed in the last 3 km from the mouth; for AL and AM, as well as for BO and CA, the cumulative data are also presented in view of their coupled treatment (grey cells).

In 2020, the prevailing land-use is still forest (up to 65 %) and the natural stands mentioned above have been integrated by artificial pine forests planted in 1950s on degraded or deforested land in order to mitigate the hydrogeological disruption affecting mountain territories; shrubland grew slightly (on average by 13 %), as well as agricultural areas (20 %) and natural grasslands in the remaining areas.

3.2. Classification of watershed-coast case studies according to the "intensity of intervention" with check dams

In order to provide a rough criterion to discriminate watersheds with a different level of "intensity of intervention" with check dams, the following parameters were calculated and compared: areal density of check dams (i.e., the number of check dams divided by the watershed area), linear density of check dams (i.e., the number of check dams divided by the total length of the mainstream), hydraulic gradient of the mainstream covered by the check dam system (i.e., the sum of check

Table 3
Coastal processes: characteristics of wave motion and sedimentology of the Tyrrhenian and Ionian coasts (Aspromonte Massif, southern Calabria).

	Watershed							
	Tyrrhenian side		Ionian side					
	GA	SA	AL	AM	TG	BO	CA	LA
Wave climate								
$H_{s,max}$ (m)	2.47	2.91	6.38	6.38	6.37	6.62	6.62	6.62
$H_{s,mean}$ (m)	0.30	0.30	0.77	0.77	0.69	0.72	0.72	0.72
$\Delta H = h_{s500} - h_{s1}$ (m)	1.46	2.05	4.04	4.04	3.8	4.14	4.14	4.14
Main sector (°)	190	180	130	130	130	130	130	130
Average annual energy flux (KW m)	0.6	0.6	6.8	6.8	5.5	6.0	6.0	6.0
Average annual energy flux of the main sector (KW m)	0.24	0.19	0.68	0.68	0.71	0.58	0.58	0.58
Sedimentology - Granulometric features[a]								
Beach	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand
Seabed 0 to −5 m a.s.l.	Very coarse sand	Very coarse sand	Medium sand	Medium sand	Medium sand	Medium sand	Medium sand	Medium sand
Seabed −5 to −10 m a.s.l.	Fine sand	Fine sand	Fine sand	Fine sand	Fine sand	Very fine sand	Very fine sand	Very fine sand
Longshore sediment transport[a] (10^3 m^3/year)	10	10	125	125	140	200	145	200

Notes: GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; H_s = significant wave height; ΔH = difference of significant wave height of fixed return period (h_{s1} and h_{s500} correspond to return periods of 1 year and 500 years respectively, to consider both frequent and rare events).

[a] Foti et al. (2022b).

dam heights divided by the altimetric range of the mainstream).

3.3. Stream subdivision into mountain, intermediate and valley reaches

According to the "alluvial cascade" approach (Bombino et al., 2006, 2007, 2022a; Montgomery and Buffington, 1997), the streams were conceptually sub-divided into three reach classes: "Mountain" (Mr), "Intermediated" (Ir) and "Valley" (Vr). To facilitate the comparability of the stream bed longitudinal profiles, the distances from the source to the mouth and the elevations were normalised using the following formula:

$$N = (X - X_{min})/(X_{max} - X_{min})$$

which allowed the values to be scaled so that they were between 0 and 1.

3.4. Evaluation of sediment volumes retained by check dam systems

The 686 check dams located in the eight watersheds were characterized using the geodatabase previously developed by several extensive investigations (80 field surveys for a total of approximately 960 h and 24,000 km travelled; A.FO.R., 1998). The sizes and volumes ($V_{S,CD}$) of the sediment wedges were calculated by applying the Prism Method (Castillo et al., 2007; Ramos-Diez et al., 2016) for each stream reach.

3.5. Evaluation of shoreline changes

The shoreline changes were detected through the cartography and satellite imagery indicated in Table 4. Accordingly, the following time-windows were taken into consideration: 1954–70s, as the first macro-campaign of intervention; 70s–80s, second macro-campaign of intervention; 80s–1996, campaign of control works integration; 1996–today.

Table 4
Reference years of the cartographic/satellite database for each watershed-coast case study.

	Watershed							
	Tyrrhenian side		Ionian side					
	GA	SA	AL	AM	TG	BO	CA	LV
1950s	1954	1954	1954	1954	1954	1954	1954	1954
1970s	1974	1976	1975	1975	n.a.	n.a.	n.a.	n.a.
1980s	1983	1983	1983	1983	1983	1983	1983	1983
1990s	1996	1996	1996	1996	1996	1996	1996	1996
Most recent	2021	2021	2019	2019	2021	2021	2021	2021

Notes: GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde;

Based on the work of Bombino et al. (2022a), the following parameters, both in linear and volumetric terms, were evaluated to assess shoreline changes in the four time-windows considered, according to the working steps indicated in Table 5:

- Estimated Beach slope (EBs): estimated by analysing the 1 m square meshed LIDAR DTMs available on the National Geoportal and by using the QGIS Profile Tool plugin; for the coastal section analysed, about ten transects were identified and for each transect the elevation profile was obtained using the plugin; the slope of the section was then assumed to be equal to the average value of the gradients of each transect;
- Longshore Changed Width (LCW): the length of the affected shoreline, determined by analysing shoreline changes on both cartography and satellite imagery;
- Linear Movement (LM): average shift (retreat or advancement) of shoreline calculated by averaging the distances between the actual coastline position and that coinciding with different time-windows considered; specifically, linear movements (retreat or advancement) were measured along the affected coastline (LCW) at survey points perpendicular to the coastline and spaced 100 m apart; finally, the median of these values was calculated (Fig. 3a);
- Area of the beach (A) in retreat (−) or advance (+), as the average variation of the beach surface, was evaluated considering the stretch of coast affected by the morphology change; the area between two subsequent shoreline profiles was then measured by QGIS;
- Estimated Volume (EV): volume of the beach in retreat (−) or advance (+); to estimate the eroded or accumulated portion of the beach it was hypothesised that the transverse profile of the beach can be schematised as a right-angled triangle (Fig. 3b), with the height equal to the main value of the maximum heights of each transect defined above; therefore, the eroded or accumulated volume can be

Table 5
Summary of working steps to assess shoreline changes at the mouth of the studied watersheds.

1st step: acquisition of cartographic data
Data source - Shapefiles of the historical shorelines of 1954 – Calabrian Geoportal Open Data section (http://geoportale.regione.calabria.it/opendata); - Orthophotos of 1996 – Web Map Service (WMS) of the Italian Geoportal Open Data section (http://www.pcn.minambiente.it/mattm/servizio-wms/); - Aerial photogrammetry at 2500 DPI from the 70s and 80s – Military Geographic Institute; - Satellite imagery from 2015 to today – Google Earth Pro.
2nd step: digitalization of each missing shoreline related to orthophotos and Google satellite imagery
Orthophotos and aerial photogrammetry - QGIS at a scale 1:1000; analysis tools of Google Earth Pro at an eye altitude of 200 m, corresponding to a higher scale, for satellite images; - Georeferencing of aerial photogrammetry using control points correspond to fixed points present in all data; this accuracy check is also important with Google satellite imagery which can be affected by uncertainties regarding its horizontal accuracy (Nikolakopoulos, 2008). **Shapefiles of shorelines of 1954** - Digitalisation based on CASMEZ “Cassa per il Mezzogiorno” 1:10000 cartography of 1954; - Generally characterized by various uncertainties, physical, scanning and georeferencing, which can be quantified according to Allan et al. (2003) and Del Río and Gracia (2013); the reference line chosen is the wet/dry; the cartography data all relate to the summer period and no storm conditions have been observed in any of the data, so the effects of seasonal variation in shoreline position and individual sea storms on shoreline change are negligible. Calabria is a microtidal environment with tidal ranges in the order of tens of centimetres (Sannino et al., 2015), so the effects of tidal excursion has been neglected.
3rd step: evaluation of corresponding volume (EV) to beach retreat or advancement
EV depends on: a) beach slope, estimated using the QGIS Profile tool plugin based on the 1 m side square mesh LIDAR DTMs available on the Italian Geoportal (http://www.pcn.minambiente.it/mattm/); b) nearshore beach slope, estimated through the QGIS Profile Tool plugin starting from the open access bathymetry available on the European Marine Observation and Data Network (EMODnet) portal (https://www.emodnet-bathymetry.eu/).

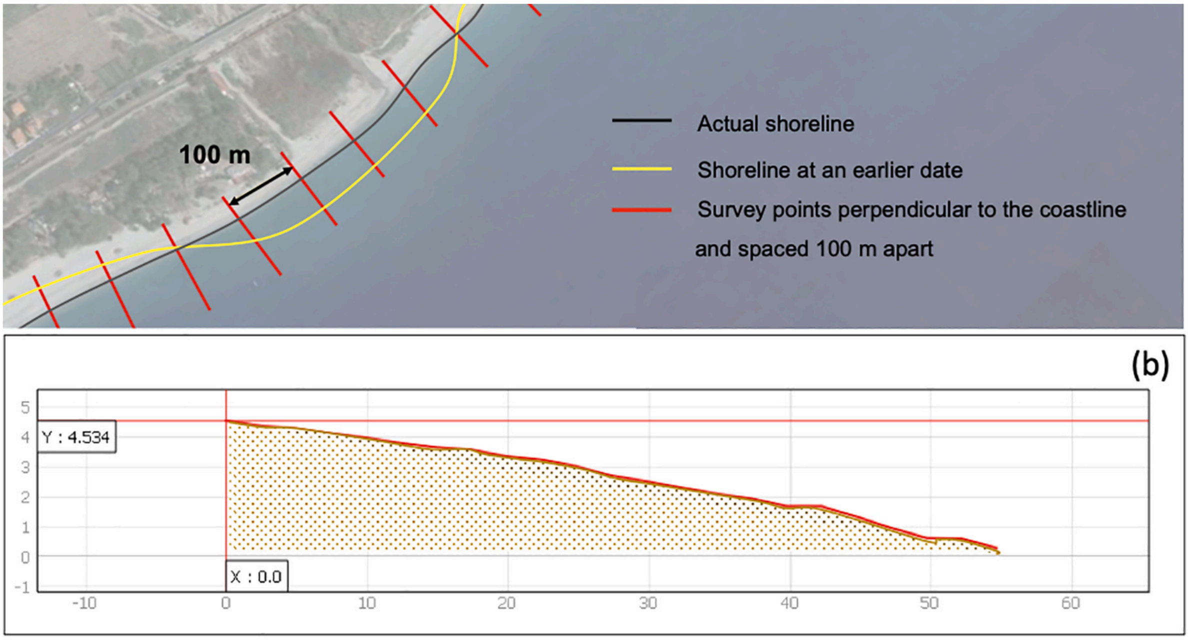
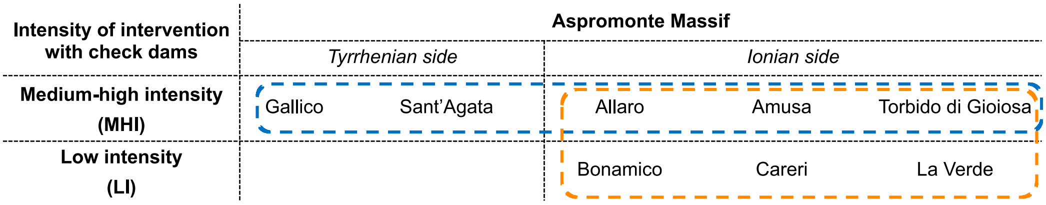


Fig. 3. (a) Sketch of the measurement method used to estimate the Linear Movement (LM); (b) transverse profile of the beach schematised on QGIS to assess the Estimated Volume (EV). Fig. 3b represents an example of the transverse profile determined at each survey point (red lines in Fig. 3a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

schematised with a figure consisting of a known base area (estimated on QGIS) and triangular cross-sections.

3.6. *Cross analysis of the results either at within or between watersheds-coast systems*

The sediment volumes retained by check dam systems ($V_{S,CD}$) were analysed in relation to the shoreline asset over time, for each watershed, both at basin scale and for each reach (Vr, Ir, Mr). In order to verify the recurrence and representativeness of the relationships with $V_{S,CD}$, comparisons were carried out both between watersheds with similar level of intensity of intervention but distinct climatic, meteo-marine and hydromorphological characteristics (being located on the opposite slopes of the Aspromonte Massif; Fig. 4, blue dashed line), and between watersheds with different level of intensity of intervention under the same conditions (Fig. 4, orange dashed line).



Intensity of intervention with check dams	Aspromonte Massif Tyrrhenian side		Aspromonte Massif Ionian side		
Medium-high intensity (MHI)	Gallico	Sant'Agata	Allaro	Amusa	Torbido di Gioiosa
Low intensity (LI)			Bonamico	Careri	La Verde

Fig. 4. Comparison scheme of the watersheds studied: the blue dotted line groups the watersheds located on the opposite sides of the Aspromonte Massif; the orange dotted line, the watersheds with different intensities of intervention under the same climatic and geomorphological conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Results

In relation to the accentuated prevalence of check dams (and, consequently, of the greater amount of sediment retained by them) in the lower part of the watersheds, the results will be presented in inverse order with respect to the stream reaches (valley, intermediate and mountain).

4.1. Splitting of watershed-coast case studies according to the "intensity of intervention" with check dams

The "intensity of intervention with check dams" resulted "medium-high" (MHI) in five cases (GA and SA watersheds on Tyrrhenian side, and AL, AM and TG on the Ionian side) and "low" (LI) in three cases (BO, CA and LV on the Ionian side) (Table 6). Overall, the MHI watersheds cover about 451 km^2 and present 675 check dams (Fig. 5) distributed from the headwater to the terminal reach, with an average height between 0.9 and 3.8 m; the LI watersheds cover about 345 km^2, with only 11 check dams (average height between 0.9 and 2.9 m) limited to the headwater.

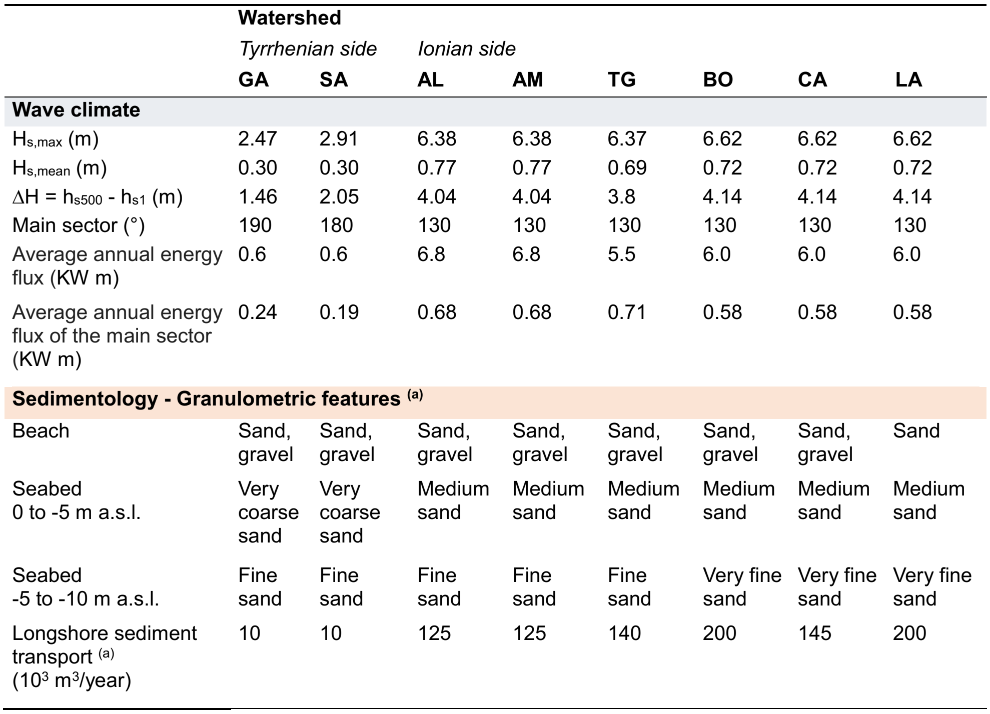
4.2. Stream subdivision into "mountain", "intermediate" and "valley" reaches

The subdivision of the mainstream into "mountain" (Mr), "intermediate" (Ir) and "valley" (Vr) reaches leads to the normalised longitudinal profiles of the riverbed shown in Fig. 6, which confirms the different morphology of the two opposite sides (S-E and N-W) of the Aspromonte system (it is possible appreciate how the Ionian slope decrease more "gently" towards the sea than the Tyrrhenian slope). The values of the normalised transition distance are shown in Table 7.

Table 8 shows the main characteristics of Vr, Ir and Mr. of each watershed in terms of length, area and altitude difference. In addition, for each reach, it shows the distribution of check dams, the areal density of the intervention (CD/km^2), the difference in elevation of torrent reach (H_R) covered by the total height of the check dams ($\Delta = \Sigma h_{CD}/H_R$) and the latter with respect to the torrent reach length (Δ/L_R).

In general (except for AM) in Vr the values of the areal density of check dams are higher than those in Mr. (up to 80 %); considering Vr and Ir together, in all cases the values are higher than those for Mr (62 %–99 %). An exception would appear to be LV (with "low intensity of intervention") which, however, has only two check dams located in the

Table 6
Intensity of intervention with check dam systems in the watershed case studies on the Tyrrhenian and Ionian sides of the Aspromonte Massif (Southern Calabria, Italy).



	Watershed							
	Tyrrhenian side		*Ionian side*					
	GA	**SA**	**AL**	**AM**	**TG**	**BO**	**CA**	**LA**
Wave climate								
$H_{s,max}$ (m)	2.47	2.91	6.38	6.38	6.37	6.62	6.62	6.62
$H_{s,mean}$ (m)	0.30	0.30	0.77	0.77	0.69	0.72	0.72	0.72
$\Delta H = h_{s500} - h_{s1}$ (m)	1.46	2.05	4.04	4.04	3.8	4.14	4.14	4.14
Main sector (°)	190	180	130	130	130	130	130	130
Average annual energy flux (KW m)	0.6	0.6	6.8	6.8	5.5	6.0	6.0	6.0
Average annual energy flux of the main sector (KW m)	0.24	0.19	0.68	0.68	0.71	0.58	0.58	0.58
Sedimentology - Granulometric features [(a)]								
Beach	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand, gravel	Sand
Seabed 0 to -5 m a.s.l.	Very coarse sand	Very coarse sand	Medium sand	Medium sand	Medium sand	Medium sand	Medium sand	Medium sand
Seabed -5 to -10 m a.s.l.	Fine sand	Fine sand	Fine sand	Fine sand	Fine sand	Very fine sand	Very fine sand	Very fine sand
Longshore sediment transport [(a)] (10^3 m^3/year)	10	10	125	125	140	200	145	200

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; for AL and AM as well as BO and CA, cumulative data are also presented in view of their coupled treatment (grey cells).

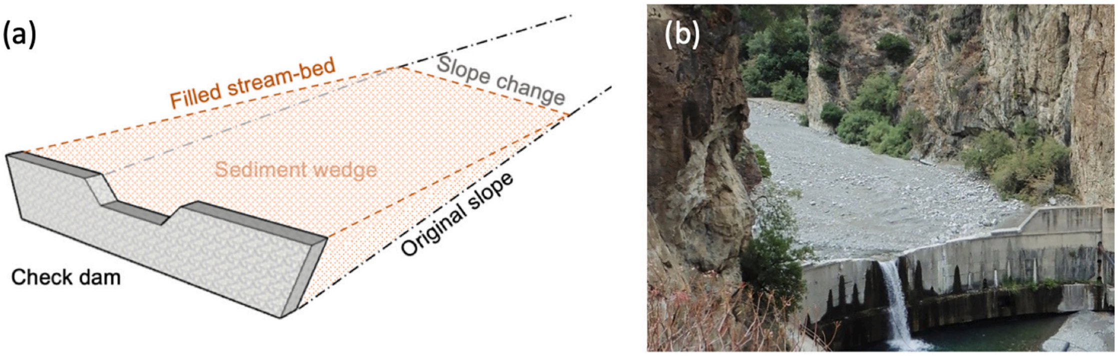


Fig. 5. (a) Sketch of a check dam and the related sediment wedge; (b) photo of a check dam completely filled upstream, located in the intermediate reach of the fiumara La Verde (LV, Ionian side).

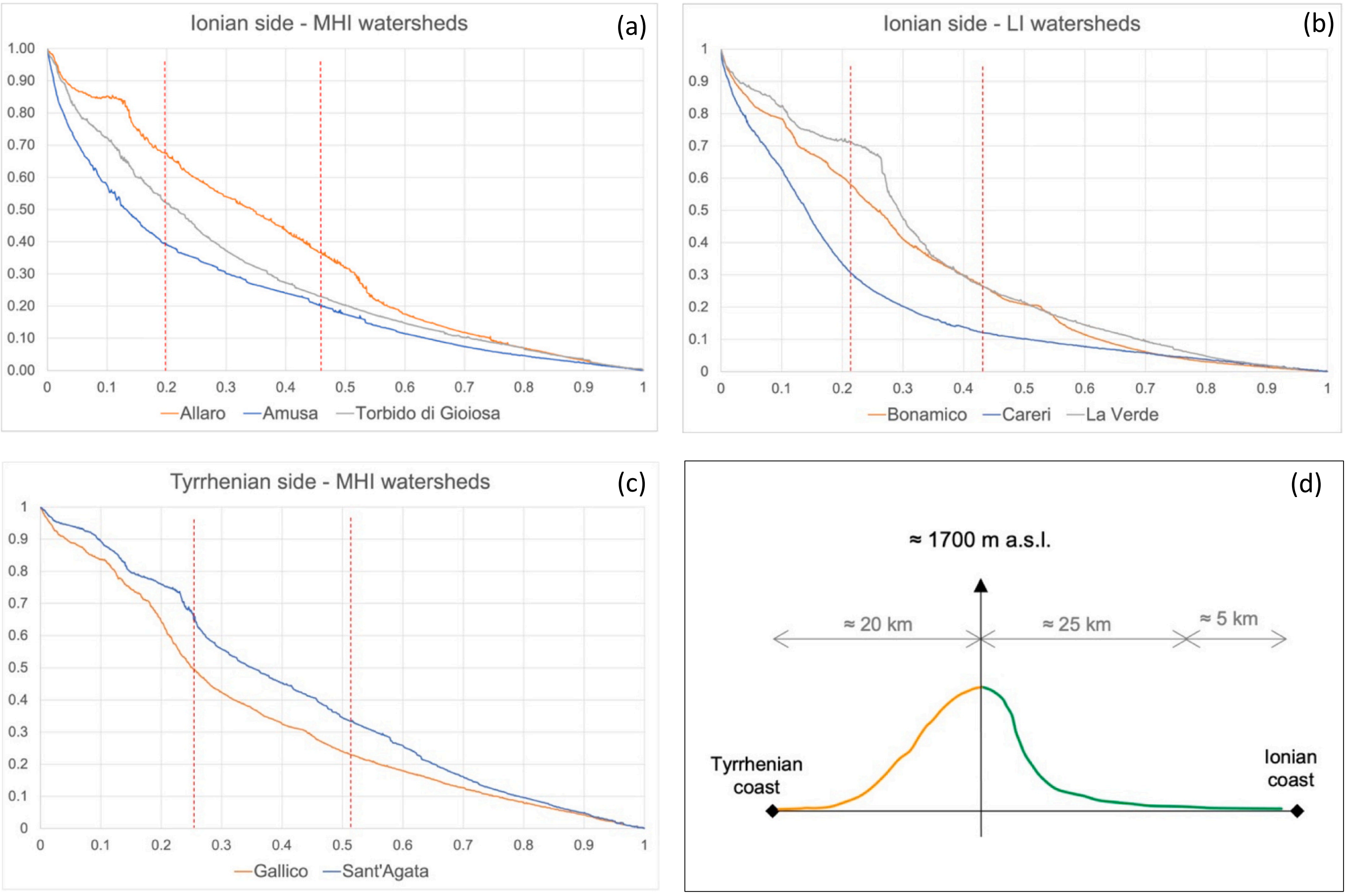


Fig. 6. Representation of the normalised longitudinal profiles of the MHI (medium-high intensity of intervention) and LI (low intensity) watersheds on the Ionian side (a, b) and of MHI watersheds on the Tyrrhenian side (c) (red dotted lines in a, b and c indicate where the change in slope occurs); (d) sketch of the elevation and extension profile of the two opposite sides of the Aspromonte system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intermediate reach on a total area of 117 km^2 (Table 8).

Within the MHI watersheds, on both the Tyrrhenian and Ionian side, the height of check dam systems (Σ h_{CD}) installed in the Vr(s) covers a difference in elevation (H_R) almost equal if not greater (up to an order of magnitude, as in the case of GA, SA and TG) than that of the Mr.(s). A similar trend is observed when considering the ratio between the previous parameter and the reach length (L_R). In addition, the slope values of settled and unsettled final reaches were measured (Table 9). They range from 2.3 to 2.8 % (regulated watersheds in the Tyrrhenian side, where the check dams caused a slope reduction of up to 30 %), from 1.6 to 2.1 % (regulated watersheds in the Ionian side; slope reduction up to 20 %) and from 1.0 to 2.6 (unregulated).

4.3. *Sediment volumes retained by check dam systems in the stream reaches*

The total sediment volume retained behind the check dams ($V_{S,CD}$) calculated for each watershed varies between 395 × 10^3 m^3 (AL) and 987 × 10^3 m^3 (GA) (Table 9).

Table 7
Normalised distances of transition between stream reaches.

	Watershed							
	Tyrrhenian side		Ionian side					
	MHI		MHI			LI		
	GA	SA	AL	AM	TG	BO	CA	LV
Mountain → Intermediate	0.28	0.27	0.14	0.19	0.25	0.18	0.18	0.27
Intermediate → Valley	0.45	0.58	0.53	0.53	0.42	0.53	0.35	0.41
Mountain → Intermediate	0.28		0.20					
Intermediate → Valley	0.52		0.46					

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde.

Table 8
Morphometric properties of torrent reaches and distribution of check dams in the studied watersheds.

		Watershed							
		Tyrrhenian side		Ionian side					
		MHI		MHI			LI		
		GA	SA	AL	AM	TG	BO	CA	LA
Reach length L_R (km)	Vr	13.0	9.7	12.5	7.0	7.8	14.0	14.4	20.1
	Ir	4.0	4.1	5.9	3.4	3.7	10.5	3.7	4.8
	Mr	6.6	8.5	12.1	6.8	6.4	5.4	4.0	9.2
	All reaches	23.6	22.3	30.5	17.2	17.9	29.9	22.1	34.0
Reach area A_R (km^2)	Vr	18.0	13.5	37.2	12.5	30.0	35.9	30.2	46.2
	Ir	17.1	12.6	11.9	5.3	39.5	72.1	30.5	37.3
	Mr	24.5	34.9	82.9	20.6	90.5	28.4	31.4	33.5
	All reaches	59.6	61.0	132.0	38.4	160.1	136.4	92.1	117.0
Difference in elevation of reach H_R (m)	Vr	468	340	172	123	171	368	607	517
	Ir	261	240	411	124	288	832	217	590
	Mr	894	760	921	628	676	704	160	714
Check dams CD	Vr	159	28	20	3	68	0	0	0
	Ir	40	37	3	16	85	0	1	2
	Mr	65	65	25	22	39	3	5	0
	All reaches	264	130	48	41	192	3	6	2
no.CD/area (CD/km^2)	Vr	8.8	2.1	0.5	0.2	2.3	–	–	–
	Ir	2.3	2.9	0.3	3.0	2.2	–	0.03	0.05
	Mr	2.7	1.9	0.3	1.1	0.4	0.11	0.16	–
	All reaches	4.4	2.1	0.4	1.1	1.2	0.02	0.07	0.02
Σh_{CD} (m)	Vr	214.6	109.6	44.7	7.6	69.3	–	–	–
	Ir	53.6	181.1	6.7	35.8	87.2	–	1.5	5.8
	Mr	87.2	306.3	55.9	49.2	40.2	2.8	5.7	–
$\Delta = \Sigma h_{CD}/H_R$ (m m^{-1})	Vr	0.459	0.322	0.260	0.062	0.405	–	–	–
	Ir	0.205	0.755	0.016	0.289	0.303	–	0.007	0.010
	Mr	0.098	0.403	0.061	0.078	0.059	0.004	0.036	–
Δ/L_R (m m^{-1} km^{-1})	Vr	0.035	0.033	0.021	0.009	0.052	–	–	–
	Ir	0.051	0.184	0.003	0.085	0.082	–	0.002	0.002
	Mr	0.015	0.047	0.005	0.012	0.009	0.001	0.009	–

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; h_{CD} = average height of check dams.

Table 9
Bed slope values *ante* (original) and *post-operam* measured in the valley reach (Vr) of the studied watersheds.

	Watershed							
	Tyrrhenian side		Ionian side					
	MHI		MHI			LI		
	GA	SA	AL	AM	TG	BO	CA	LV
Vr original slope (%)	3.2	3.3	2.1	2.4	1.6	2.6	1.0	2.5
Vr new slope (%)	2.3	2.8	1.7	2.0	1.4	2.6	1.0	2.5
Check dams in Vr	159	28	20	3	68	0	0	0

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde.

4.3.1. *Valley reaches*

The greatest average width of the check dams (from 77 m in SA to 133 m in AM) and the highest value of the structure height (from 3 m in AL to 4 m in TG) were recorded in the Vr. The average sediment wedge lengths range from 136 m (GA) to 254 m (SA) and are systematically higher up to about 5 times than in the Mr. The lowest average wedge slope values of 1.5 % were observed in Vr. The sediment volume retained in Vr is systematically higher than in Ir and Mr., up to two and four times respectively (Table 10).

Within the MHI watersheds, on both the Tyrrhenian and Ionian side, transverse structures installed in Vr trap on average 55 % of the total sediment volume retained by check dam systems within the whole watershed (Table 10).

4.3.2. *Intermediate reach*

On average, the width and height values of check dams vary from 30.5 to 59.7 m and 1.3 to 2.9 m respectively. The average length of

Table 10
Check dam characteristics and sediment wedge size and volume ($V_{S,CD}$) data for each stream reach in the studied watershed.

		Watershed								Total
		Tyrrhenian side		Ionian side						
		MHI		MHI			LI			
		GA	SA	AL	AM	TG	BO	CA	LV	
Check dams										
Average width	Vr	86.3	76.9	94.2	132.7	106.2	–	–	–	
(m)	Ir	41.3	32.4	45.4	59.7	48.2	–	30.5	34.8	
	Mr	10.9	8.0	11.3	15.6	13.7	7.4	9.4	–	
Average height	Vr	3.3	3.7	2.9	3.4	3.8	–	–	–	
(m)	Ir	1.6	1.6	1.3	1.6	1.8	–	1.5	2.9	
	Mr	0.9	0.9	0.8	0.9	1.0	0.9	1.1	–	
Sediment wedge										
Average length	Vr	135.7	254.4	198.4	197.0	215.7	–	–	–	
(m)	Ir	79.7	87.8	95.5	76.6	80.3	–	58.0	97.0	
	Mr	23.8	24.3	29.0	25.1	31.8	19.8	21.3	–	
Average slope	Vr	0.014	0.015	0.012	0.015	0.004	–	–	–	
(m m^{-1})	Ir	0.061	0.061	0.061	0.063	0.014	–	0.056	0.068	
	Mr	0.181	0.198	0.206	0.180	0.051	0.189	0.169	–	
Sediment volume										
$V_{S,CD}$	Vr	542.6	236.8	217.1	273.2	541.0	–	–	–	
(10^3 m^3)	(Range)	0.3÷3	0.9÷8	1÷10	10÷81	0.9÷1	–	–	–	
	Ir	296.0	129.2	118.4	149.0	295.1	–	0.9	2.9	
	(Range)	0.8÷7	0.3÷3.5	4÷35	1÷8	0.4÷4	–	0.9	1.2; 1.7	
	Mr	148.0	64.6	59.2	74.5	147.5	1.1	2.5	–	
	(Range)	0.2÷2	0.1÷0.9	0.3÷2	0.3÷3	0.4÷3.2	0.3÷0.6	0.2÷0.9	–	
	All reaches	987.0	430.5	395.0	496.7	983.6	1.1	3.4	2.9	3292.1
	(Range)	0.4÷4	0.3÷3	0.9÷8	1÷11	0.5÷5	0.3÷0.6	0.2÷0.8	1.2; 1.7	0.1÷81

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde.

sediment wedge varies from 58 m (CA) to 97 m (LV) and is generally higher (up to about 3 times) than that observed in Mr. The average wedge slope values vary from 1.4 % (TG) to 6.8 (LA). The sediment volume retained in Ir is systematically higher than in Mr., up to two times (Table 10).

Table 11
Morphological shoreline changes near the mouths of the investigated watersheds during each campaign of check dam realisation, in terms of average linear movement (LM), longshore changed width (LCW), beach area (A) and volume (EV) affected by retreat/accretion.

Linear and areal characteristics of shoreline over time	Watershed					
	Tyrrhenian side		Ionian side			
	MHI		MHI		LI	
	GA	SA	AL + AM	TG	BO + CA	LV
Estimated beach slope (%)	10.4	6.4	4.9	7.3	7.6	7.5
1954–70s				*1954* ————————> *1983*		
LM (m)	−36	+25	−80	(maps from the 1970s are not available)		
LCW (m)	850	400	2800			
A (−/+) (10^3 m^2)	−17	+5	−150			
EV (−/+) (10^3 m^3)	−24.5	+4.1	−190.5			
1970s–80s						
LM (m)	−43	−60	−90	−90	−3	+4
LCW (m)	600	1500	3000	4000	4000	4700
A (−/+) (10^3 m^2)	−12	−50	−115	−130	−10	+20
EV (−/+) (10^3 m^3)	−16.5	−41.3	−146.1	−296.0	−15.0	+25.0
1980s–90s						
LM (m)	−21	+50***	−105	−10	−6	−2
LCW (m)	600	1400	4100	1000	2600	3500
A (−/+) (10^3 m^2)	−19	+55	−160	−8	−25	−14
EV (−/+) (10^3 m^3)	−14.5	+45.4	−203.2	−17.1	−36.3	−17.5
1990s–today						
LM (m)	+7* // +21**	+20	−30	−10	+30	+11
LCW (m)	700	200	5300	1800	2200	3500
A (−/+) (10^3 m^2)	+10	+2	−100	−9	+45	+46
EV (−/+) (10^3 m^3)	+13.5	+1.7	−127.0	−20.5	+65.3	+57.5

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; *with/**without rock breakwater barrier; ***drastic narrowing, rectification and cementing of the riverbed in the last three kilometres from the mouth.

4.3.3. Mountain reach

On average, the width and height of the check dams are about 12 and 0.9 m respectively (Table 10). The average length of sediment wedge varies from 19.8 m (BO) to 31.8 (TG). As expected, the highest values of wedge slope were observed in the mountain reaches (from 5.1 % to 20.6 %).The sediment volume retained behind the check dam systems varies from 1.1 × 10^3 (BO) to 148.0 × 10^3 m^3 (GA).

4.4. Shoreline changes at the mouth of the studied watersheds in relation to the sediment volumes trapped by check dam systems

The changes in shoreline morphology for each watershed-coast system, in terms of average linear movement (LM), longshore changed width (LCW), beach area (A) and beach sediment volume (EV) affected by retreat/accretion are reported in Table 11 (considering the four time-windows) and in Table 12 (considering the entire observed period). For the TG, BO, CA and LV watersheds (on the Ionian side) the first values in the table cover the 1954–1983 time-window (as already mentioned, maps from the 1970s are not available). Fig. 7 shows an example of Google satellite images analysed to assess the change in shoreline morphology near the mouths of the studied watersheds.

At the end of the second time-window (1980s, corresponding to the first and second macro-campaigns of intervention) all the MHI watersheds show a retreat in terms of LM varying from −35 m (SA) to −170 m (AL-AM), with losses of EV varying from −37.2 × 10^3 m^3 (SA) to −337 × 10^3 m^3 (AL-AM), and width of the affected longshore up to 4000 m (TG).

This trend is also confirmed at the end of the third time-window (80s–90s), except for the SA where a trend towards advancement is observed after the channelling and cementing of the riverbed in the valley reach (LM = +50 m, EV = +45.4 × 10^3 m^3).

At the end of the fourth time-window (*1990s*–today) the retreating trend continues for AL-AM and TG watersheds, while GA (after the construction of the rock breakwater barriers) and SA show a slight advancing trend (LM = +7 m and EV = +13.5 × 10^3 $m^3$for GA; LM = +20 and EV = +1.7 × 10^3 m^3 for SA).

On the contrary, at the end of the second time-window (80s) the LM of the watersheds on the Ionian side (with “low intensity of intervention”) is substantially unaffected (LCW >4000 m).

At the end of the third time-window (80s–90s) BO-CA and LV show LM = −6 m and −2 m respectively, with EV values up to −36.3 × 10^3 m^3 for BO-CA and −17.5 × 10^3 m^3 for LV. The strangely recorded shoreline retreats for BO-CA and LV are probably due to the fluvial stone extraction cycles, which, especially since 1978, have been very intense.

At the end of the last time-window (90s–today) the LI watersheds show an advancement in terms of LM, with values of +30 m for BO-CA and +11 m for LV.

Figs. 8 and 9 allow an easier joint analysis of the data on the average linear movement (LM, Table 11) along the identified longshore changed width (LCW, Table 10) and the volume of beach retreated or advanced (EV, Table 11), in relation to the number of check dams (CD, Table 8) and the sediment volume retained behind the structures ($V_{S,CD}$, Table 10), in the four time-windows considered.

The Fig. 8 clearly shows the LM trend in relation to the construction of check dams over a 70 years period. In the MHI watersheds, both on the Tyrrhenian and Ionian sides, after the two macro-campaigns of intervention (from 1954 to 70s, and from 70s to 80s), when >85 % of the check dams were completely filled, the highest retreat values were recorded, although the trend also continues in the third and fourth integrative campaigns (80s–1996 and 1996–today), up to a maximum of −230 m (AL-AM). In the LI watersheds, on the other hand, there is a tendency to advance over time, according to the low number of installed check dams (a total of nine in BO-CA and two in LV).

Fig. 9 shows a comparison between the calculated sediment volumes retained by the check dams ($V_{S,CD}$) and the estimated volumes of beach retreat or advance, which confirms both the trend observed in Fig. 8 and the different tendency between the MHI and LI watersheds. In fact, all MHI watersheds show beach retreat with volume values up to 670 × 10^3 m^3 (AL-AM). Overall, the check dam systems of GA and AL-AM retained comparable amounts of sediment volume (990 × 10^3 m^3, GA; 892 × 10^3 m^3, AL-AM); however, the EV are significantly different with values of 42 × 10^3 m^3 and 667 × 10^3 m^3 respectively, highlighting the protective effects of rock breakwater barriers installed near the mouth of the GA. The LI watersheds, instead, once completed the short-term effects of the check dams (second time-window for BO-CA and first for LV), show a clear advancement of shoreline.

With particular reference to the valley part of the watersheds, the results highlight how check dams installed in the Vr retain >50 % of the total volume retained in the watersheds (Table 13).

Table 14 reports the grain-size characteristics and surface sediments variation along the mainstreams (from headwater to mouth) for each torrent studied. In particular, 12 cross-section were sampled for each reach (mountain, intermediate, valley) not affected by check dams, and three for the mouth (n = 39); moreover, each cross-section was divided in six sample areas (n = 6, three on the right and three on the left of the thalweg). In addition, the cross-sections immediately upstream (within the sediment wedge) of three check dams in the mountain, intermediate and valley reach were also analysed (n = 54, 6 sample areas × 3 check dams × 3 reaches).

The data refer both to several survey campaigns (Bombino et al., 2008; Ferro and Porto, 2011, 2012; Porto and Gessler, 1999; Viparelli, 1963; Viparelli and Maione, 1959) carried out on the same streams (appropriately extrapolated and elaborated) and to specific surveys (still in progress) carried out by us.

Comparison of mean diameter values (of both fine and gravelly fraction) and D90 shows that there are no statistically significant differences ($p < 0.05$) between the sediments retained by the check dams within the Vr (Table 14) and those present on the beach (see the

Table 12

Morphological shoreline changes near the mouths of the investigated watersheds after the extended campaigns of check dam realisation, in terms of average linear movement (LM), longshore changed width (LCW), beach area (A) and volume (EV) affected by retreat/accretion.

	Watershed							
	Tyrrhenian side		Ionian side					
	MHI		MHI			LI		
	GA	SA	AL	AM	TG	BO	CA	LV
Estimated beach slope (%)	10.4	6.4	4.9	7.3	7.6	7.5	10.4	6.4
1954–today								
LM (m)	−93	35	−305		−110	21		13
LCW (average value) (m)	688	875	3800		2267	2933		3900
A (−/+) (10^3 m^2)	−38	12	−525		−147	10		52
EV (−/+) (10^3 m^3)	−42.0	9.9	−666.8		−333.4	14.0		65.0

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; EBs = estimated beach slope.

Fig. 7. Google satellite images analysed to assess shoreline morphology near the mouths of the watersheds studied.

parameter/values identified with the same letters in the table). This means that the sediment immobilised by the structures would have contributed to the beach nourishment if the check dams had not retained them in the valley reach (Fig. 10); instead, this material is subtracted from the shoreline dynamic and, therefore, from the sediment mass balance. In general, the finer fractions can be observed (i) above the sediment wedge in the form of bars, (ii) trapped by "island of vegetation" colonising the wedge or (iii) immobilised by "pioneer island" developing around sediements deposited or protecting a strip of an aggrading sediment. Only floods with a high return time can transport finer sediments downstream, causing the wedge to flatten and its height to drop to that of the structure.

This phenomenon is further confirmed by comparing the average diameter (of both fine and gravel fractions) and D90 values measured in the portions of the riverbed far from the transverse structures and those at the mouth. In this case, the comparison shows a statistically significant difference ($p < 0.05$) between the samples (different letters in the table), meaning that the finer sediment moving downstream reach the beach or are immobilised behind the check dams.

Tyrrhenian side - MHI watersheds

GALLICO

Note: during the IV time-window (90s–today) the rock breakwater barriers were constructed.

SANT'AGATA

Note: during the III time-window (80s–90s) there was drastic narrowing, rectification and cementing of the riverbed in the last 3 kilometres from the mouth.

Ionian side - MHI watersheds

ALLARO and AMUSA

TORBIDO DI GIOIOSA

Ionian side - LI watersheds

BONAMICO and CARERI

LA VERDE

Fig. 8. Comparison between the number of check dams (CD) and the average linear movement of the shoreline (LM) during the four time-windows: (I) 1954–1970s; (II) 1970s–80s; (III) 1980s–90s; (IV) 1990s–today.

5. Discussion

Check dams, as is well known, are transverse control works specifically designed for the regulation of headwaters and mountain reaches (Ferro, 2002), where the steep slopes and the energetic characteristics of the water flow favour erosive processes and hydraulic disorder (Abbasi et al., 2019; Bombino et al., 2022b; Castillo et al., 2007; Conesa-García et al., 2007; Piton and Recking, 2016; Quiñonero-Rubio et al., 2016; Romero-Díaz, 2008). Therefore, in these contexts, to mitigate the hydrological instability phenomena, there are no easy alternative measures and intervention other than check dams (weirs).

Nevertheless, the MHI watersheds (medium-high intensity of intervention) are characterized by the higher presence of transverse hydraulic engineering works in the Vr(s) (up to 3.5 times more than in

Note: during the IV time-window (90s–today) the rock breakwater barriers were constructed.

Note: during the III time-window (80s–90s) there was drastic narrowing, rectification and cementing of the riverbed in the last 3 kilometres from the mouth.

Fig. 9. Comparison between the calculated sediment volumes ($V_{S,CD}$) retained by check dam systems and the estimated volumes (EV) resulting in shoreline retreat/advancement, during the four time-windows: (I) 1954–1970s; (II) 1970s–80s; (III) 1980s–90s; (IV) 1990s–today.

headwaters; Table 8), where the natural riverbed slope is in itself very low and would have suggested alternative techniques to control the stream dynamics and reduce hydraulic risk, facilitating if nothing else the sediment movement towards the mouth. In this regard, the slope values of settled and unsettled final reaches of the eight watersheds investigated were measured (Table 9). They range from 2.3 to 2.8 % (regulated watersheds in the Tyrrhenian side, with slope reduction up to 30 %), from 1.6 to 2.1 % (regulated watersheds in the Ionian side, where check dams caused slope reduction up to 20 %) and from 1.0 to 2.6 (unregulated watersheds).

Specific investigations carried out by Bombino et al. (2022a) in the lower reach of the GA (last 2 km up to the mouth), regulated with 21 check dams, showed that the check dams fill up completely in a short period (<5 years), confirming what has also been observed by other

Table 13
Sediment volumes retained by check dams ($V_{S,CD}$) in the valley reach (Vr) compared with the total sediment volume retained at watershed scale.

	Watershed							
	Tyrrhenian side		Ionian side					
	MHI		MHI			LI		
	GA	SA	AL	AM	TG	BO	CA	LV
$V_{S,CD}$ in Vr (10^3 m^3)	542.6	236.8	217.1	273.2	541.0	0.0	0.0	0.0
Total $V_{S,CD}$ in the watershed (10^3 m^3)	987.0	430.5	395.1	496.7	983.6	1.1	3.4	2.9

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde.

Table 14
Granulometric characteristics (average diameter and D90) of the sediment surveyed along the mainstreams of the studied torrents far from (n = 234) and near (n = 18, only in the Vr) the check dams.

		Watershed							
		Tyrrhenian side		Ionian side					
		MHI		MHI			LI		
		GA	SA	AL	AM	TG	CA	BO	LV
Far from check dams									
Mountain (n = 72)									
Average diameter	Fine	1.98	1.94	1.98	1.96	1.97	2.00	1.97	1.98
(mm)	St. dev. (+/−)	0.4	0.5	0.5	0.4	0.4	0.4	0.6	0.5
	Gravel	51.3	34.7	39.3	38.6	34.1	51.8	49.3	47.6
	St. dev. (+/−)	3.9	3.6	3.2	3.1	2.9	3.6	4.1	3.7
D90	Mean	124.6	117.2	122.3	212.8	117.4	126.6	124.2	119.1
(mm)	St. dev. (+/−)	9.1	8.7	9.6	10.7	9.1	9.6	9.6	8.8
Intermediate (n = 72)									
Average diameter	Fine	2.12	1.87	1.91	1.93	1.87	2.03	1.98	1.83
(mm)	St. dev. (+/−)	0.4	0.5	0.4	0.4	0.3	0.4	0.4	0.3
	Gravel	49.6	31.5	32.9	31.7	33.1	49.6	48.7	46.2
	St. dev. (+/−)	3.6	3.5	2.8	2.8	3.0	3.2	3.9	3.5
D90	Mean	85.7	78.3	84.5	82.8	79.6	83.7	84.1	80.6
(mm)	St. dev. (+/−)	7.2	6.0	7.8	9.3	6.7	6.5	6.5	6.2
Valley (n = 72)									
Average diameter	Fine[a]	1.88	1.44	1.60	1.69	1.71	1.98	1.91	1.78
(mm)	St. dev. (+/−)	0.5	0.4	0.3	0.3	0.4	0.4	0.4	0.5
	Gravel[b]	45.8	32.8	28.8	29.8	30.7	45.9	43.8	43.6
	St. dev. (+/−)	3.3	3.2	2.7	2.6	2.4	2.9	3.3	3.2
D90	Mean[c]	50.1	38.8	47.6	41.3	42.3	49.4	44.1	43.7
(mm)	St. dev. (+/−)	4.8	4.6	5.4	5.8	4.8	4.6	4.4	4.4
Mouth (n = 18)									
Average diameter	Fine[d]	1.52	1.29	0.96	1.07	1.08	1.51	1.39	1.50
(mm)	St. dev. (+/−)	0.5	0.4	0.3	0.4	0.5	0.4	0.6	0.5
	Gravel[e]	35.1	24.7	22.4	22.6	23.0	33.4	33.6	20.9
	St. dev. (+/−)	3.0	2.9	2.6	2.5	2.3	2.7	3.0	3.0
D90	Mean[f]	37.2	24.2	33.2	31.1	31.3	38.4	34.9	22.8
(mm)	St. dev. (+/−)	3.1	2.8	2.9	3.0	2.6	2.5	2.5	2.5
Immediately upstream of check dams									
Average diameter	Fine[d]	1.46	1.23	0.94	1.03	1.04	–	–	–
(mm)	St. dev. (+/−)	0.5	0.5	0.3	0.3	0.3	–	–	–
	Gravel[e]	34.6	24.1	22.1	22.4	22.4	–	–	–
	St. dev. (+/−)	2.8	2.7	2.2	2.1	2.0	–	–	–
D90	Mean[f]	36.7	24.0	32.7	30.6	30.8	–	–	–
(mm)	St. dev. (+/−)	2.9	2.1	2.8	2.8	2.8	–	–	–

Notes: MHI = medium-high intensity of intervention; LI = low intensity of intervention; GA = Gallico; SA = Sant'Agata; AL = Allaro; AM = Amusa; TG = Torbido di Gioiosa; BO = Bonamico; CA = Careri; LV = La Verde; [a, b, c, d, e,] and [f]: these letters are used to indicate the parameters/values for which a statical analysis was performed; where parameters have the same letter, this means that they do not show statistically significant differences.

authors (Bombino et al., 2022b; Viparelli, 1972); this was further demonstrated by monitoring (in the same valley reach) the filling dynamics of 13 check dams rebuilt after their collapse caused by an extreme flood event. The 21 check dams installed in the final section of the GA trapped a total of 71.4 × 10^3 m^3 of sediment; on the other hand, the settled final reach tends to rise systematically exceeding the level of the embankments, so that it must be periodically recalibrated; in fact, during 2015, it was necessary to recalibrate the stream bed in order to reduce the impending hydraulic risk; 56 × 10^3 m^3 of sediment were removed along the entire reach, but 5 years later, a detailed longitudinal profile survey compared with the plano-altimetric profile survey carried out before the operation showed that as much as 40 × 10^3 m^3 of sediment had again redeposited. The sediments removed as a result of the intervention have been committed to the dump, since Italian Law strongly restricts their reuse for beach nourishment when (i) there is a danger that they may be contaminated by pollutants, (ii) a specific study on the geomorphological, fluvial landform and sedimentological dynamics/evolution of the riverbed has not been carried out, or (iii) there

Fig. 10. Fine sediment trapped behind the check dam installed near the mouth of the fiumara Gallico.

is no sediment management plan approved by the District Basin Authority (Law 152/2006, Environment Code as amended and supplemented; EU Framework Directive 98/2008; Regional Law of 29 June 2016).

Observations highlight that in the short term (5 years) the amount of sediment trapped by the check dams (71.4×10^3 m^3) seems to have a significant impact on the sediment balance at the mouth but, however, it is to be considered a “one-off”. The sediment that is deposited due to the reduced slope of the reach caused by check dam systems has a long-term effect (an average of 8×10^3 m^3 per year in the terminal reach alone), and therefore has a greater impact on the sediment balance at the mouth and, therefore, on the dynamics of the shoreline. At the same time-window shoreline at the mouth of GA lost approximately 15×10^3 m^3.

The values measured in the final reach seem to be compatible with the sediment transport estimated by using the erosion potential model (Gavrilovic, 1959), which provided for entire GA watershed an average value of 50×10^3 m^3 per year (values of the same order of magnitude have been found in the Aspromonte and Serre mountain systems investigating watersheds of similar extent) (Barbaro et al., 2021).

It would seem, therefore, that the slope of the terminal reach (and, consequently, the water velocity and its transport capacity) plays a fundamental role on the evolution of the shoreline, since the percentage of sediment that nourishes the coastline depends on it.

As well known, check dams (weirs) are specifically installed to reduce energy gradients, due to the decrease in the riverbed slope. The reduced gradients favour the deposition of finer particles in addition to the coarse fractions typical of the pre-existing (ante operam) riverbed. But in the valley reaches, the natural slope of the riverbed is already low, so there should be no transverse works that can interrupt the connectivity and flow of sediments, impeding them from reaching the mouth.

Once the check dams are completely filled in and the riverbed has reached a new slope (so called equilibrium slope), it often happens that dense riparian vegetation settles in the sedimentation wedge (Bombino et al., 2006). The combined effect of the reduction of the slope and the presence of vegetation promotes both the deposition of the finer particles above the sediment wedge in the form of bars, and the formation of areas of vegetation that trap them as they pass. Only floods with a high-return period can remove the sediments behind check dams, flattening the sediment wedge and lowering it to that of the structure.

In general, it would appear that even a reduction of a fraction of a percentage point in the slope in the final reach could have caused a retreatment of the shoreline, over a period of about 70 years, in watersheds with “medium-high intensity of intervention”.

Shoreline changes at the mouth of the studied watersheds, in relation to the sediment volumes trapped by check dam systems, highlights values comparable to those found in the regulated watersheds by other

Authors under similar environmental and climatic conditions. Aiello et al. (2013), for example, comparing two time-windows 1870–1954 (before river regulation) and 1954–2005 (after river control works installation) in the Ionian coastline of South Italy, demonstrated average shoreline net movement of +110 m and −30 m respectively, resulting similar to the values presented in this study. Also in Southern Italy, with respect to the same time-windows, Scorpio and Rosskopf (2016), investigating the shoreline change in a regulated Mediterranean river (with check dams), confirmed retreatment up to −160 m (1954–1976) and −155 m (1976–1998).

Overall, at the end of the entire observation period (1954–2022) a shoreline retreat was generally recorded for the MHI watersheds (Table 12), confirming a clear cause-effect relationship between the gradual implementation of the regulation campaigns and the shoreline changes.

A separate reasoning deserves SA that represent an exception to this phenomenon: starting from the third integrative campaign (1980s), it shows a counter-trend (accretion). This is probably due to the rectification, narrowing and concreting of the last few kilometres of the riverbed (at the mouth) to increase hydraulic safety in view of the extension of the airport runway that crosses the watercourse. These interventions have modified the energy characteristics of the water flow of the fiumara (reduction of the hydraulic roughness, increase of unit flow rate, resulting in higher velocity and transport capacity) and continue to favour the arrival of sediment transported from upstream to the mouth.

The fact that the check dams (weirs) installed in the Vr retain more than half of the total sediment retained by the check dam system of the entire watershed, clearly indicates an influence of the transverse works on the flow of sediment towards the mouth and, consequently, on the shoreline evolution. The granulometric analysis clearly suggest that the finer fractions trapped within and above the sediment wedge forming behind the structures installed in the valley reaches would have contributed to nourishment of the beach if it had not been by the check dams.

This effect makes questionable the use of check dams (weirs) in the lower part of the watershed and suggests how it would be necessary to pay attention towards a renewed approach, not only to avoid the raising of the riverbed (and, consequently, the increase of the overflooding risk), but also to optimize the sediment connectivity according to the watershed-coast *continuum* (Marchi et al., 2019).

6. Conclusion

A sample of eight watershed-coast systems in Southern Calabria, Italy, was analysed, extending a previously developed evaluation methodology. The eight case studies fall under the different climatic, physiographic and meteo-marine conditions of the opposite Tyrrhenian and Ionian sides of the Aspromonte Massif system Here, the effects of a varying intensity of intervention with check dams (as a result of the implementation of the progressive torrent regulation campaigns started about 70 years ago) on shoreline dynamics were observed and analysed, both in terms of shoreline retreat/advancement and eroded beach volume.

6.1. Shoreline retreat/advancement

The results of the investigation confirm the recurrence and relevance of the shoreline retreat phenomenon at the mouth of the regulated watersheds with medium-high intensity of intervention, including the Gallico watershed-coast system studied in a previous work. The highest observed value of affected longshore is just over 5 km (about 7 times the width of the cross-section of the affected mouth). A maximum shoreline retreat of 170 m (1.4 % of the valley reach length) was also observed. The results for shoreline changes are comparable to those reported by other Authors under similar climatic conditions and intensity of intervention. Minor retreats (up to 10 m) were observed at the mouth of the low-regulated watersheds (with do not have check dams in the valley reach).

6.2. Beach volume

For regulated watersheds with medium-high intensity of intervention, eroded beach volumes of $>660 \times 10^3$ m^3 were estimated; in the low-regulated watersheds, on the other hand, natural accretion or negligible beach volume losses were recorded. The phenomenon appears correlated to the level of intervention intensity with check dams, with short-term effects produced by the rapid immobilization of large amounts of sediments behind the transverse structure and long-term effects as a result of the reduction of the streambed longitudinal slope and the related sediment transport capacity of stream flow. Finer material may accumulate for several years above the sediment wedge; occasionally (return period >5 years) it is removed by the passage of floods and transferred downstream supplying the mouth. With the passage of infrequent floods, the sediment wedge flattens and its level drops to the height of the structure; current laws do not allow the removal and the transfer to the mouth of the sediments trapped by the check dams and accumulated in the sediment wedge.

6.3. The influence of check dams installed in the lower reaches

The phenomenon of shoreline retreat, in particular, suggests that particular attention should be paid to the installation of check dams in the valley reach of torrents: the detected incidence in terms of retained sediment volume is on average >50 % compared to the whole regulated watercourse, and it is historically known that the control of headwater and mountain reaches whit check dams is often indispensable.

6.4. Strengths and weaknesses of the investigation

It was ensured that some coastal processes and dynamics that govern the phenomenon (e.g. wave energy and sea currents) act homogeneously at the mouths of the watersheds that fall on the same side (and which were used for comparison). Nevertheless, the methodology employed, not taking into account other driving factors (such as tides, submarine morphology facing the watershed mouth, tectonic phenomena, land-use changes in the catchment areas), could be a useful tool for investigating and assessing the influence of the installation of check dams on the evolution of the shoreline asset.

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CRediT authorship contribution statement

Giuseppe Barbaro: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Daniela D'Agostino:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Pietro Denisi:** Writing – original draft, Formal analysis, Data curation. **Giandomenico Foti:** Writing – review & editing, Validation, Investigation, Data curation. **Santo Marcello Zimbone:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The used data are reported in the paper.

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