BOMBINO, G., Barbaro, G., D'Agostino, D., Denisi, P., Foti, G., Labate, A., & Zimbone, S. M. (2022). Shoreline change and coastal erosion: The role of check dams. First indications from a case study in Calabria, southern Italy. *Catena*, *217*, 106494. DOI: 10.1016/j.catena.2022.106494.

POST-PRINT ONLY

SHORELINE CHANGE AND COASTAL EROSION: THE ROLE OF CHECK DAMS. FIRST INDICATIONS FROM A CASE STUDY IN CALABRIA, SOUTHERN ITALY

Giuseppe Bombino[1]*, Giuseppe Barbaro[2], Daniela D'Agostino[1], Pietro Denisi[1], Giandomenico Foti[2], Antonino Labate[1], Santo Marcello Zimbone[1]

[1]University *Mediterranea* of Reggio Calabria, Department of AGRARIA, Loc. Feo di Vito, 89122, Reggio Calabria, Italy

[2]University *Mediterranea* of Reggio Calabria, Department of Civil Engineering, Energy, Environment and Materials, Loc. Feo di Vito, 89122, Reggio Calabria, Italy

giuseppe.bombino@unirc.it; giuseppe.barbaro@unirc.it; daniela.dagostino@unirc.it;

giandomenico.foti@unirc.it; pietro.denisi@unirc.it; a.labate@unirc.it, smzimbone@unirc.it

*corresponding author: giuseppe.bombino@unirc.it

POST-PRINT ONLY

Abstract

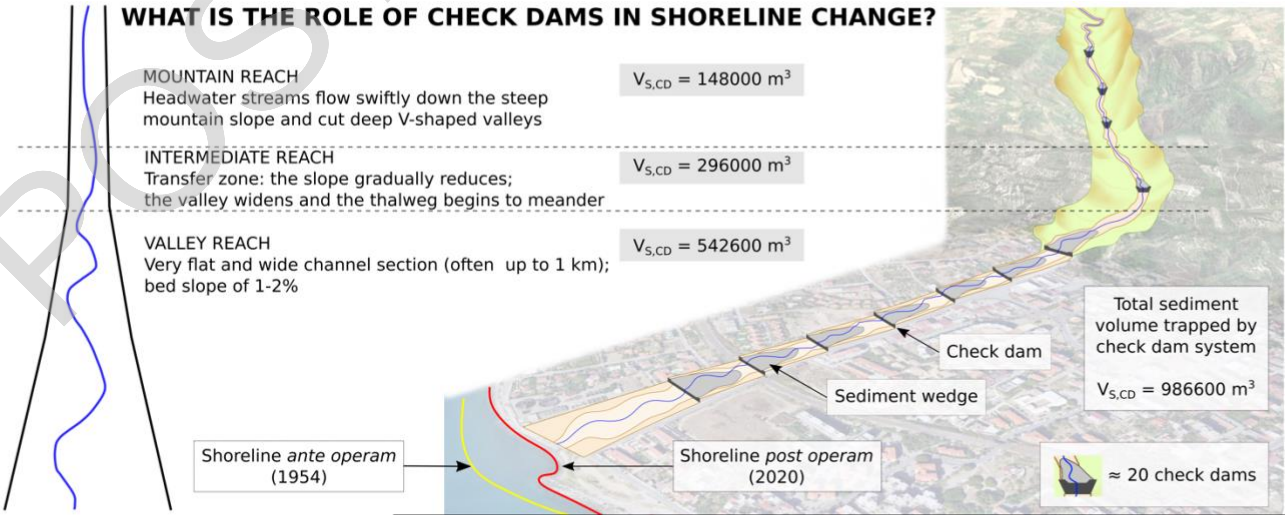
Currently, most of the world's coastal territories are subject to erosive processes, often caused by an alteration of sediment balance due to both natural and anthropogenic factors. This issue is relevant in many Mediterranean territories such as Calabria region, in southern Italy. Here, considerable anthropogenic pressures affect about 750 km of coast on which debouch short torrential rivers locally termed 'fiumare'. The regional climate, hydrology and geomorphology leads to intensive *fiumare* catchment erosion and high fluvial solid loads.

The work focuses on the Gallico *fiumara*, chosen as case study affected by an intense hydraulic regulation programme in order to investigate the poorly studied effects of engineering control works on shoreline changes.

The paper has considered the effects of the 264 check dams (completely filled a few years after their realization) only investigating the relationships between the volume retained by the structures and shoreline change during the several arrangement campaigns. Although the work does not consider the other processes that explain the complexity of the watershed-coast sediment balance, it has been clearly demonstrated an influence of check dam system on the evolution of the shoreline, especially due to the hydraulic works installed in the lower part of the watershed. In the light of the results obtained, it would be desirable to promote a debate on the opportunity to convert or demolish the check dams in the torrent reaches closest to the coast, where, moreover, the engineering control most reduced the already limited natural riverbed slope.

POST-PRINT ONLY

Graphical Abstract



Keywords

Fiumara, Shoreline, Check dam system, Sediment storage, Coastal erosion

POST-PRINT ONLY

1. Introduction

Rivers and streams play a key role in sediment production and cascading, transferring and/or buffering fluxes from headwaters and mountain reaches to downstream alluvial environments (Fryirs, 2013). The amount of sediments (naturally fluctuating in time) transferred from rivers to the coastal system determines a mass balance that has large effects on the position and morphology of the shoreline (Anthony et al., 2015, 2014; Falqués, 2006; Leeder, 1999; Limber et al., 2008; Warrick, 2020; Willis and Griggs, 2003).

On the one hand, the amount of solid material from watershed is strongly related to the rapid hydrological responses typical of upland environments, in combination with the sediment availability. More specifically, sediment production depends on the combination of natural (e.g. climate, morphogenetics and geodynamics, geo-lithology and geomorphology, vegetation cover) and anthropogenic factors (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; Piton et al., 2017). The latter can act directly (e.g. hydraulic engineering control works, such as check dams) or indirectly (e.g. land use change) on the alteration of water and sediment dynamics within the catchment. On the other hand, the dynamics regulating the coastline morphology are also influenced by natural (e.g. sea level rise resulting from climatic change, rainfall, sea storms and flood events, geological and lithological changes; (Dean, 2002; Leeder, 1999; Tsimplis et al., 2005; Tsimplis and Baker, 2000; Velegrakis et al., 2008; Vousdoukas et al., 2007) and human interventions (e.g. maritime constructions; Pilkey and Dixon, 1996), which overlap with those already mentioned and which alter the sediments supply over time (Poulos et al., 2000; Stanley and Warne, 1998).

Concerning fluvial control works, in particular check dams, all over the world and also in the Mediterranean area the scientific community is facing a heated debate on their environmental impacts and effectiveness. In addition to the several effects within the watershed (e.g. on channel stability, sediment control, riparian ecosystem and biodiversity, bed scouring, etc.) the impacts of check dams on shoreline retreat have been demonstrated due to the local storage and lowering of the sediment transport capacity to the coast (Acciarri et al., 2016; Aiello et al., 2013; Batalla, 2003; Boix-Fayos et al., 2007; Coltori, 1997; Kondolf, 1997; Kuleli, 2010a; Martínez del Pozo and Anfuso, 2008; Miao et al., 2010; Rosskopf et al., 2018a; Wang et al., 2012; Xu, 2005; Zhao et al., 2017).

Recent researches have established that 85% of river deltas around the world have shrank during the first decade of the 21st century due to sediment retention by soil-water conservation measures (e.g. sediment check dams) in upstream reaches (Miao et al., 2010; Wang et al., 2012; Xu, 2005; Zhao et al., 2017). Partly

POST-PRINT ONLY

because of this, the public opinion is inclined to consider channel regulations of streams and rivers as the cause of shoreline changes due to sediment flow modification.

Shoreline retreat along the central and southern coast of Italy (more than 940 x 10^3 m^2, with an average net shoreline movement of -30 m, over a period of 60 years from 1954 to 2014) as a result of human interventions has been observed (Acciarri et al., 2016; Rosskopf et al., 2018), confirming what has also been observed in other geographical areas (Batalla, 2003; Kondolf, 1997; Kuleli, 2010; Martínez del Pozo and Anfuso, 2008). Here, moreover, the effects of the check dams installation occurred since the second half of the 20th century have been detected (Aiello et al., 2013; Boix-Fayos et al., 2007; Coltori, 1997), and it would appear that the most significant effects have been observed at the installation of control works in the lower river courses (Rosskopf et al., 2018b). However, quantitative studies are still scarce.

In the literature there are not many studies that consider separately the impacts of upstream and downstream regulation on the evolution of the coastline, also because of the difficulty to discriminate the effects within a physiographic unit characterised by the interconnection of processes (*continuum*) that regulate the sediment flow and its mobilisation (from upstream to downstream).

To this end, through the application to a case study, this paper aims to increase knowledge on the assessment of the influence of a sequence of check dams (installed from headwaters to lower part of the watershed) on morphological and dynamic variations of the shoreline. The work also investigates separately the sediment retention effects of check dams in the different parts of the watershed (upstream, intermediate and downstream), and then assesses in detail the impact of works located closer to the coastline.

Check dams in Calabria

Calabria region (Southern Italy) synthetizes in a paroxysmal way the join action of natural (aggressive climate and hydro-geomorphology) and anthropic (human activities, unsustainable soil management and land use change) factors. Here, the peculiar kind of torrents, named *fiumara* (Bombino, 2020), can generate disruptive floods events mixed with large amount of sediment (Ballesteros-Canovas et al., 2020; Bombino et al., 2009; Fairbridge, 1968; Viparelli, 1972). Some of these extreme events happened in Calabria in the second half of 20th century, showing extraordinary characteristics in terms of both intensity (up to 160 mm h^{-1}) and duration (up to 535 mm in 24-h) (Aceto et al., 2016; Caloiero et al., 2008; Petrucci and Pasqua, 2013, 2012).

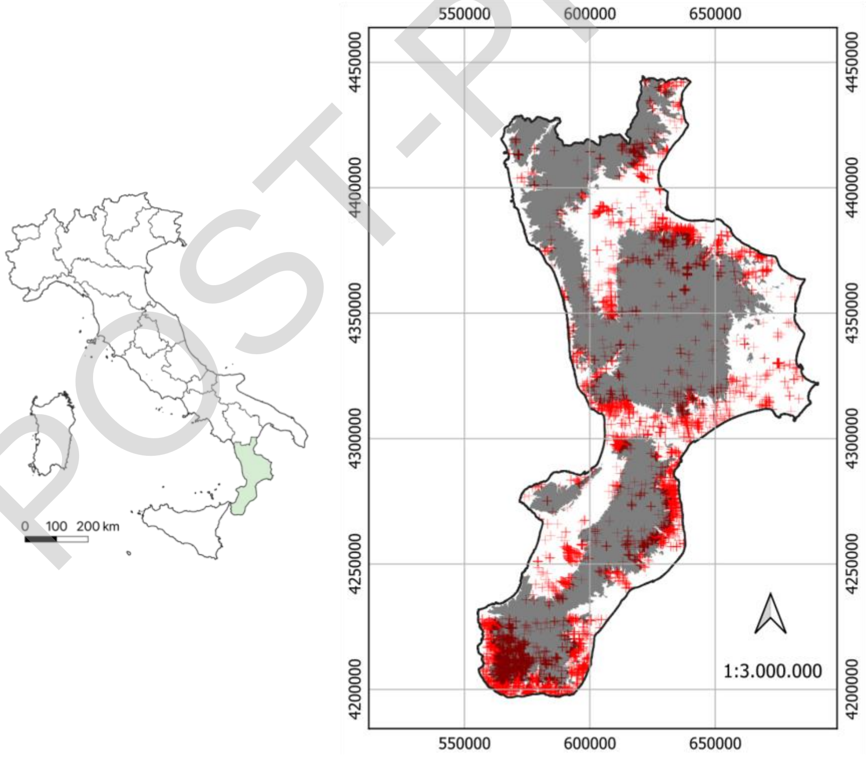
Indeed, because of several dramatic and devastating episodes which destroyed many settlements, favouring the occurrence of important economic and human losses, causing casualties and inducing many people to

POST-PRINT ONLY

leave definitively their villages (Sabato and Tropeano, 2004; Sorriso-Valvo et al., 1995), in the early 1950s Special Laws for Calabria region were issued by Italian Government and expensive investments funded a program of protection works aimed both at mitigating river floods and reclaiming swampy areas (Acerbo, 1937; Bevilacqua, 1987; Medici, 1954; Petrucci and Polemio, 2007; Ruini, 1913). Later, in the early 70s, further investments were added to the previous, for the regulation of watersheds and for slope stabilization of hilly and mountain areas, as well as relocation of the flooded population.

The total investment from the 1950s to the 1970s, discounted to 2020 (ISTAT), would have been equivalent to about 8 billion euros, and was used for the construction of hundreds of kilometres of embankments, about 150000 hectares of reforestation, and more then 8000 check dams, according to a basin scale integrated approach (A.FO.R., 1998; D'Ippolito et al., 2013; Petrucci and Polemio, 2007).

A large number of catchments have been intensely regulated with check dams from upstream to downstream, especially in the area of the Strait of Messina (southern of the region) as shown in the Fig. 1. At regional scale, considering the total number of check dams installed within each watershed, it is observed that about the 2/3 of these is concentrated in the lower areas of the basins, from the sea level up to 350 m (P.A.I.). Over time this has caused the raising of the river bed (due to the immobilization of huge amounts of sediment, Bombino et al., 2022; Sabato and Tropeano, 2004), with a consequent increase in hydraulic risk and modification of the coastline.



POST-PRINT ONLY

Fig. 1. Location of check dams (red symbols) in the lower areas (from 0 to 350 m a.s.l.; in white) of the Calabria region (Data sources: A.FO.R., 1998; 'Azienda Calabria Verde'; D'Ippolito et al., 2013; Petrucci and Polemio, 2007).

Check dams should be specifically constructed in the headwaters and torrent mountain reaches (Abbasi et al., 2019; Bombino, 2009; Castillo Sanchez et al., 2007; Heede, 1986, 1967; Piton and Recking, 2016; Quiñonero-Rubio et al., 2016; Yazdi et al., 2018) to control sediment transport (Catella et al., 2005; Conesa García, 2004; Conesa-García et al., 2007; Serrato and Díaz, 2005) and stabilise slopes and torrential channels (Conesa García, 2004; Conesa-García et al., 2007; Romero-Díaz, 2008) where erosion and solid transport phenomena are more accentuated because of the steep slopes of the riverbed and hillsides, in order to mitigate the hydrogeological risk in valley areas. Therefore, while in the headwaters and torrent mountain reaches check dams are generally unavoidable, in the lower reaches (where the watercourse has a very low natural slope) the installation of transversal control works appears somewhat questionable.

By analysing on a small scale the link between longshore and river transport over the last 60 years, the influence of hydraulic control works (particularly check dams) on coastal dynamics and shoreline evolution near the mouth of some rivers or torrents has been demonstrated (Barbaro et al., 2019; Foti et al., 2022a, 2022b). However, further and in-depth investigations are need in order to verify the recurrence of these relationships. Therefore, due to its long history of hydraulic control works (Antronico et al., 1998; Petrucci and Polemio, 2007) and the large number of intensely regulated catchments, the Calabria region is a very interesting case study for the entire Mediterranean and European area.

2. Methodology

In order to carry out a preliminary evaluation of the influence of a check dam system installed in the watershed on the variation and morphological dynamics of the coast, the following steps were taken: (i) analysis of intensively regulated watersheds, and selection of a case study with check dam sequence (from upstream to downstream) among those data on sediment volumes trapped by structures are available; (ii) division of the selected watershed into three parts (mountain, intermediate and valley, as suggested by several Authors, e.g. Lane, 1955; Montgomery and Buffington's, 1997) in order to (iii) analyse the check dam distribution/localization and calculate the amount of sediment volumes retained by structures in each part of the catchment, (iv) assess the shoreline change near the mouth of the studied watershed, and (v) identify possible relationships between the check dams and shoreline changes.

POST-PRINT ONLY

2.1 Selection of the case study

Among all those intensively regulated, the Gallico *fiumara* (Fig. 2) has been selected, showing 264 check dams over an area of 55.5 km^2 (about 5 check dams for square kilometre). The watershed has a maximum altitude of 1770 m a.s.l., a mean altitude of 704 m a.s.l. and a mean slope value of 26%; the length of main stream is about 21 km. It is characterised by hot Mediterranean climate and semiarid conditions ("Csa", according to the Köppen classification, Kottek et al., 2006), stable geomorphology with torrential hydrological regime, and his morphology can be classified as 'alluvial cascade' according to Montgomery and Buffington (1997). Geology consists of metamorphic rocks and Pleistocene gravels. In the upper part of watershed land use consists mostly of forest with shrublands, natural grassland and natural forests.

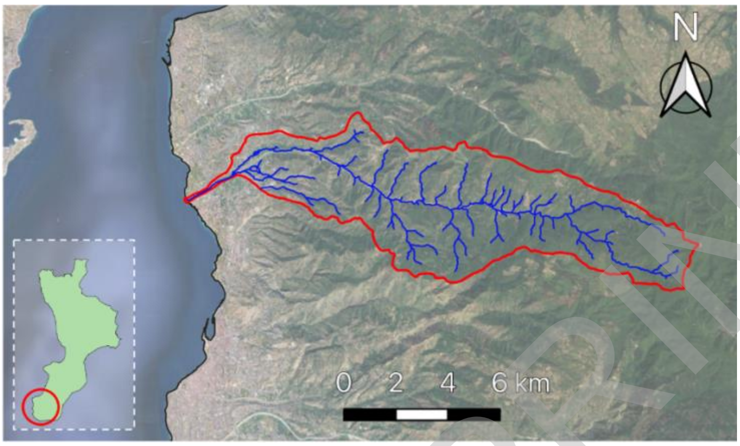


Fig. 2. Location of Gallico watershed (south Calabria, Italy).

2.2. Division of the watershed into three parts

To study in detail the distribution of check dams within the studied watershed and their effects in terms of trapped sediments volume, a longitudinal subdivision of the river environment was implemented.
Three "torrent reaches" called "mountain" (Mr), "intermediated" (Ir) and "valley" (Vr) reaches (Bombino et al., 2007, 2006) were identified, according to the 'alluvial cascade' approach proposed by Montgomery and Buffington's (1997) and by other several Authors (e.g. Kondolf, 1995; Lane, 1955; Leopold and Maddock, 1953). In particular, adopting the conceptual models they suggested, the three torrent reach types have been classified on the basis of changes in terms of geomorphology (e.g. width, depths, bed slope, grain size, bedforms, pattern), physical processes (e.g. degrading headwater channels that are primary source of sediment and water input, stable mid channels with roughly balanced inputs and outputs, and aggrading channels characterised by depositional floodplain), and climatic and ecological response (Dietrich et al.,

POST-PRINT ONLY

1989; Dietrich and Dunne, 1978; Gilbert, 1914, 1887; Gomi et al., 2003; Helley and LaMarche, 1973; Kellerhals et al., 1976; Montgomery and Buffington, 1998, 1997; Powell, 1875; Schumm, 1977; Williams, 1978). The three torrent reaches were identified by analysing the longitudinal profile of the case study: both main stream length and elevation values have been normalised within a specific range to allow a better representation. Therefore, the values were scaled to lie between 0 and 1, by using the following formula:

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

where X is the original value, X_{min} and X_{max} are its minimum and maximum values respectively, and N is the standardised value.

This approach was also integrated with observation on the structure and organization of the riparian habitat along the riverbed (form the mouth to the source). Moreover, length, area and difference in elevation of each reach were calculated.

2.3. Analyses of check dam distribution/localization and calculation of the amount of sediment volumes retained by structures in each part of watershed

During previous surveys (Bombino et al., 2022) the 264 check dams installed along the Gallico torrent were detected; sediment wedge dimensions and related volumes ($V_{S,CD}$) were calculated by applying the Prism Method (Castillo et al., 2007; Ramos-Diez et al., 2016), as reported in Table 2.

Following, both the distribution of check dams and the related $V_{S,CD}$ were attributed to each part of the watershed (mountain, intermediate and valley torrent reach).

2.4. Assessment of shoreline change near the mouth of the studied watershed

Diachronic cartographies, multi-temporal orthophotographs and satellite maps (Table 1) were analysed in order to evaluate the shoreline morphology and dynamics near the mouth of the torrent. The space-time data analysis was carried out by comparing the shoreline position *ante* and *post* the first and the second extended land conservation campaign realised over a period of about 70 years in Calabria.

For this purpose, reference was made to the period 1954-2020, divided into two the time-windows: (i) 1954-1996 referring to the period of construction of the check dams; (ii) 1996-2020, which refers to the period after the completion of the intense construction of the works and takes into account the long-term effects of them. Within the first time-window, three further sub-periods were analysed: 1954-1967, 1967-1974 and 1974-1983. In detail:

POST-PRINT ONLY

- the shapefile of the 1954 shoreline, available on the Calabrian Geoportal, has been digitised on the basis of the 1954 CASMEZ ("Cassa del Mezzogiorno") cartography, in scale 1:10000;
- the shorelines of 1967, 1974 and 1983 have been digitised by using QGIS software at a scale of 1:1000, based on the black and white aerial photogrammetry at 2500 DPI acquired by the Military Geographic Institute;
- the shoreline of 1996 has been digitalised by using QGIS software at a scale of 1:1000, based on the black and white orthophoto available on the Web Map Service (WMS) of the Open Data section of the Italian Geoportal;
- the shoreline of 2020 has been digitised by using the spatial analysis functions of Google Earth, with an eye altitude of 200 m corresponding to a scale greater than 1:1000.

The digitization process has the purpose of identifying the correct shoreline. This process is based on photointerpretation, so the choice and the extraction of a common line used for different images is required. There are many reference lines representing the shoreline position (Boak and Turner, 2005). In this paper, due to the varying oceanographic conditions among the different cartographies, the reference line chosen was the wet/dry line. This line divides the dry and wet parts of the beach and closely approximates the High-Water Line (HWL, Moore, 2000). In addition, fixed points such as promenades, roads, and structures were chosen as baselines. Table 1 also shows data relating to years that are not included in the two time-windows above mentioned. These data were not used to carry out a detailed analysis like the one just described, but only to qualitatively evaluate the shoreline evolutionary trend.

Table 1 Diachronic cartographies, multi-temporal orthophotographs, maps and satellite images analysed for the evaluation of the shoreline morphology near the mouth of the Gallico watershed.

Data source	Years	Typology
Historical shoreline cartographies and mapping	1954, 1998, 2000, 2008	Open Data section of the Calabrian Geoportal (http://geoportale.regione.calabria.it/opendata)
Aerial photogrammetry	1967, 1974, 1983	Military Geographic Institute (https://www.igmi.org/it/geoprodotti#b_start=0)
Orthophotos	1989, 1996, 2006, 2012	Open Data section of the National Geoportal (http://www.pcn.minambiente.it/mattm/servizio-wms/)
Satellite images and maps	2015, 2017, 2018, 2020	Google Earth

Both the shoreline position over time and the related variation for each time-window near the mouth of the Gallico *fiumara* has been identified and evaluated by integrating the methodological approach proposed by Aiello et al. (2013), Barbaro et al. (2019) and Foti et al. (2019). The change in shoreline morphology near the

POST-PRINT ONLY

mouth was assessed both in terms of maximum linear movement “LM” - perpendicular to the shoreline - and accretion/retreat of the littoral area over time. The average variation of the beach surface was evaluated considering the stretch of coast affected by the morphology change. In particular, to estimate the “LM” (and its average value) in the 1996-2020 time-window, because of the presence of rock breakwater barrier, two different measurements (with and without the structure) were carried out.

The beach slope was estimated by analysing the 1 m side square mesh LIDAR DTMs available on the National Geoportal and using the plugin Profile Tool QGIS. For the analysed coastal section about ten transects were identified and for each transect the elevation profile was obtained by means of the plugin. The slope of the section was then assumed to be equal to the average value of the gradients of each transect.

Finally, to estimate the beach portion eroded or accumulated (in terms of volume, “EV” = estimated volume) it has been hypothesised that the transverse profile of the beach can be schematised as a rectangular triangle, 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 schematised with a figure consisting of a known base area (estimated on QGIS) and of triangular cross-sections. According to several Author (e.g. Del Río and Gracia, 2013; Moore, 2000; Morton, 2008) the estimation of typical measurement errors and uncertainties relating to mapping methods, original data sources and shoreline digitising such as the physical component of the error, the scanning error and the georeferencing error has been evaluated. Finally, since Calabria is a microtidal environment with tidal ranges in the order of tens of centimetres (Sannino et al., 2015), its effects on the variation of the shoreline position are negligible.

In Fig. 3 some methodological steps for processing the shoreline morphological change are summarised (Barbaro et al., 2019).

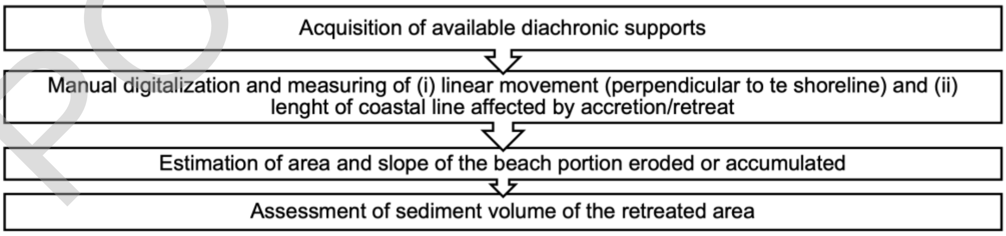


Fig. 3. Methodological phases to assess the shoreline morphological changes near the mouth of the watershed (elaborated by Barbaro et al., 2019).

POST-PRINT ONLY

2.5. Determination of possible relationships between check dams (and retained sediment volumes) and shoreline change

In order to investigate possible cause-and-effect relationships between the hydraulic control works (and the related sediment volumes trapped behind check dams) and the change in shoreline position (in terms of linear movement and sediment volumes detracted/arriving at the river mouth over time), the existing correlations were verified both for the entire watershed and for each part in which it was divided. Moreover, to quantify the influence that the check dams installed in each torrent reach (Mr, Ir, Vr) had on coastal dynamics in terms of sediment volumes removed/arrived at the river mouth, a linear regression analysis was carried out.

3. Results

3.1. Division of the watershed into the three parts

Fig. 4 shows a normalised representation of the longitudinal division of the river environment in the three torrent reaches. It is clear how the average slope of the main stream changes moving from valley to intermediate and from this latter to mountain reach; this change is observed in correspondence of a normalised distance from the watershed outlet of about 0.4 and 0.6 respectively.

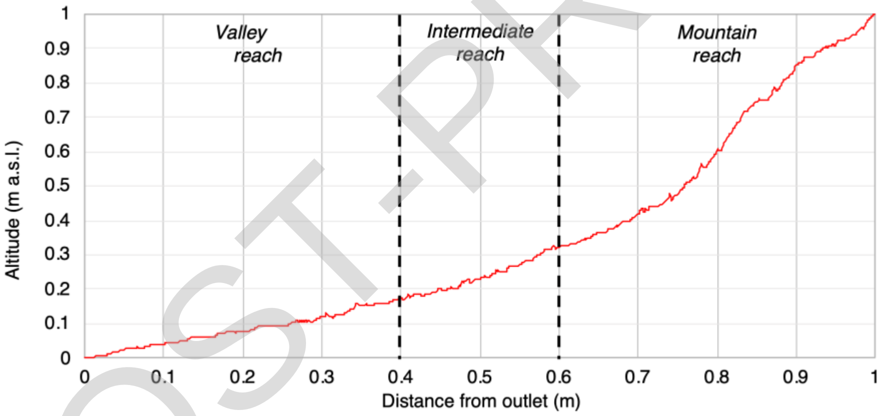


Fig. 4. Longitudinal profile of the Gallico *fiumara* and identification of the three torrent reaches (Mr, Ir, Vr).

The values of length (L_R), area (A_R) and difference in elevation (H_R) of each reach are shown in Table 2. It was observed that the mean percentage values of the watershed area portions related to Vr, Ir and Mr are 25.7%, 30.8% and 43.5%, respectively.

3.2. Check dam distribution and calculation of the related sediment volumes in Vr, Ir and Mr

POST-PRINT ONLY

The highest value of number of check dams (CD) per km^2 has been recorded in the Vr: the structures present are about 60% of the works built in the whole catchment (Table 2). Generally, the total height of check dams (Σ h_{CD}) fills about 88% of the difference in elevation of the Vr; in Mr this percentage is lower than 7%.

The total $V_{S,CD}$ in the Vr represents, on average, about the 55% of the total volume trapped in the whole watershed (987 x 10^3 m^3). The sediment wedges have an average length of about 80 m and average slope of 0.085 m m^{-1}.

Table 2. Main morphometric properties of torrent reaches (Vr, Ir, Mr); check dams distribution and related dimension and volumes ($V_{S,CD}$) of sediment wedges data in the Gallico watershed.

			All reaches	**Mr**	**Ir**	**Vr**
Torrent reach	L_R	km	17.4	5.9	3.8	7.7
	A_R	km^2	55.5	24.1	17.1	14.3
	H_{TR}	m	-	1200	160	242
Check dams	CD	-	264	65	40	159
	no.CD/area	-	4.8	2.7	2.3	11.1
	Σ h_{CD}	m	355.4	87.2	53.6	214.6
	Σ $h_{CD}/H_{TR} = \Delta$	m m^{-1}	1.31	0.09	0.33	0.89
	Δ/L_R	m m^{-1} km^{-1}	0.218	0.015	0.088	0.115
	Average width	m	46.2	10.9	41.3	86.3
	Average height	m	2.0	0.9	1.6	3.3
Sediment wedges	Average length	m	79.7	23.8	79.7	135.7
	Average slope	m m^{-1}	0.085	0.181	0.061	0.014
	$\mathbf{V_{S,CD}}$	10^3 m^3	986.6	148	296	542.6
		range	0.4 ÷ 4	0.2 ÷ 2	0.8 ÷ 7	0.3 ÷ 3

Note: L_R = reach length, A_R = reach area, H_{TR} = difference in elevation of reach, h_{CD} = check dam height.

3.3. Assessment of shoreline change near the mouth of the studied watershed

Figs. 5 show some aerial photogrammetry, digitalised orthophotos and Google satellite images analysed to evaluate the shoreline morphology near the mouth of the Gallico watershed. As you can see, those relating to the years 1967, 1974 and 1983 are unusable for assessing shoreline change. Moreover, Figs. 6 and 7 show the elaboration used to estimate LM and its mean value.

POST-PRINT ONLY

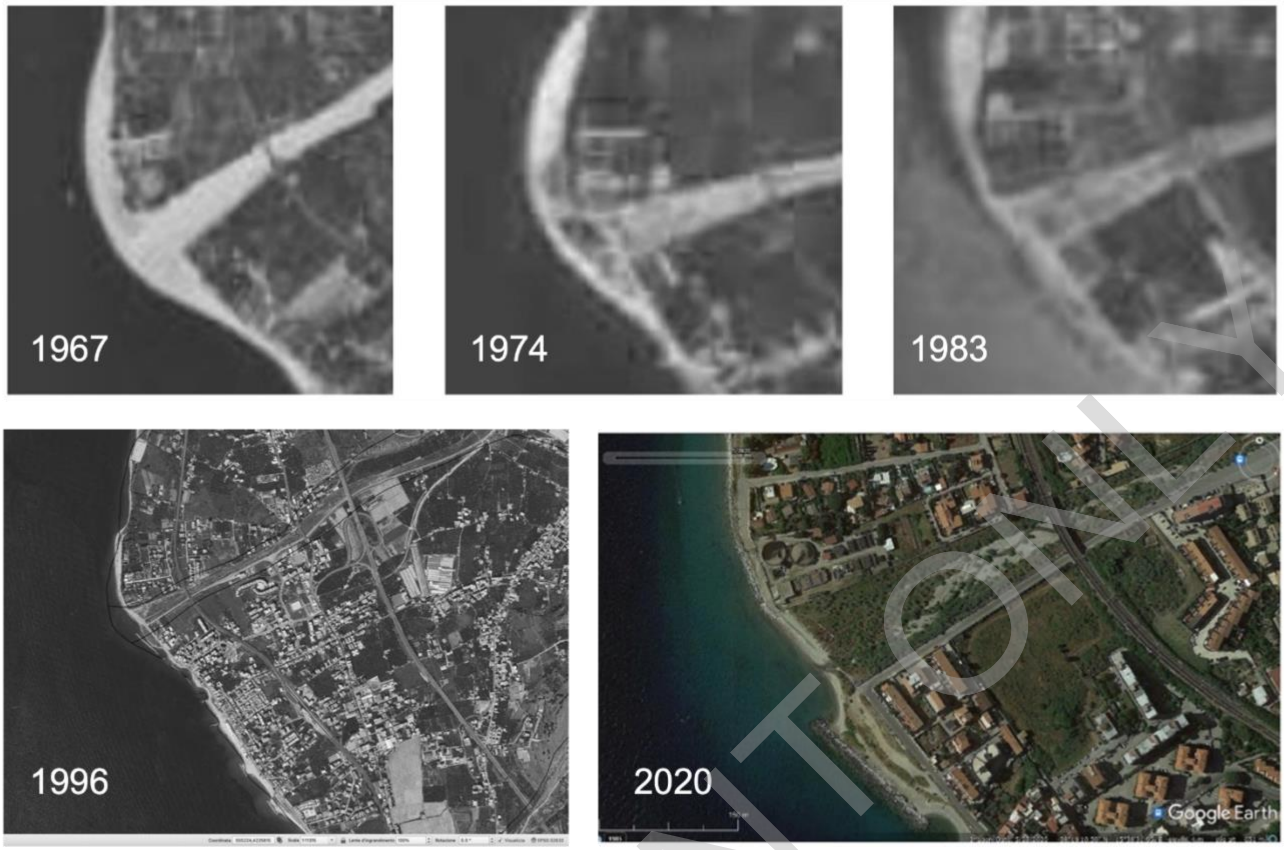


Fig. 5. Aerial photogrammetry of 1967, 1974 and 1983; digitalised orthophotos of 1996; Google satellite images of 2020.

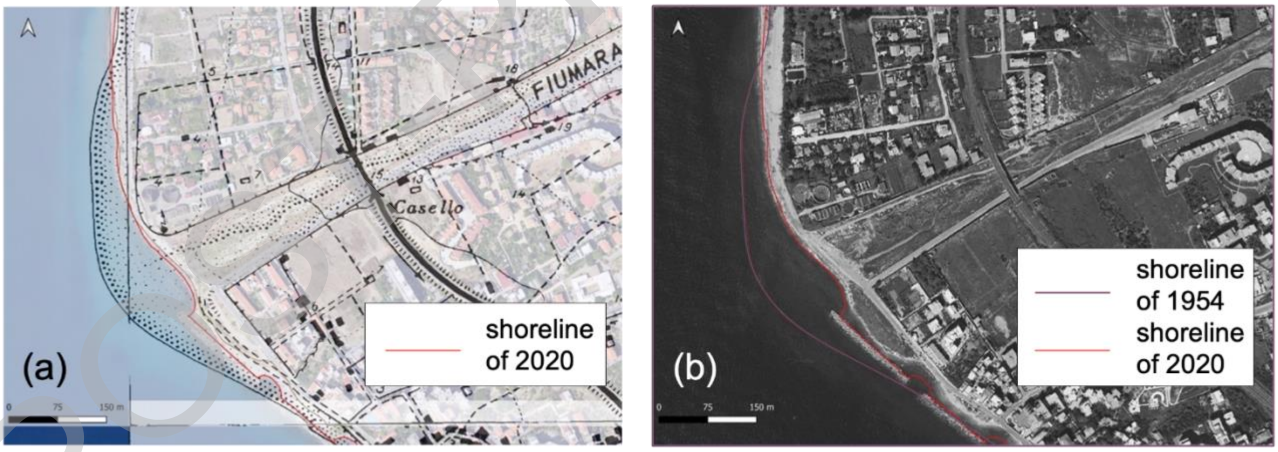


Fig. 6. (a) Overlap between 1954 CASMEZ cartography and Google satellite image of May 2020 and (b) orthophoto of 1996.

PREPRINT ONLY

Fig. 7. Historical shorelines near the mouth of Gallico *fiumara*; background Google satellite image of May 2020.

During the whole studied period (1954-2020) there has been a change in the shoreline morphology due to significant erosion processes near the mouth: there was a change from retreat (during the extended campaign of check dam installation, 1954-1996) to advancement (after the end of regulation programmes, 1996-2020). At present, since the beginning of the intensive river regulation, at the mouth of the Gallico *fiumara*, the area of the beach "A" has been reduced by a total of about 38 x 10^3 m^2 and the related evaluated volume "EV" by about 54.5 x 10^3 m^3. The reduced area concerns the beach in front of the mouth, for a length of about 150 m, and the parts of the beach to the north and to the south of the mouth, for a length of 350 m to the north and of 200 m (in 2020) and of 400 m (in 1967) to the south. Therefore, the length of the disturbed section (henceforth referred to as longshore changed width, "LCW") is reduced from 900 to 700 m (Tables 3 and 4).

Furthermore, it is highlighted that the 14 m difference between the two cases with and without breakwater (Tables 3 and 4), represents the width of the breakwater itself.

POST-PRINT

Table 3. Morphological changes of shoreline near the mouth of the Gallico *fiumara* from 1954 to date.

			1954 →				
			1967	**1974**	**1983**	**1996**	**2020**
Number of years			13	20	29	42	66
No. CD	Reach	Mountain	46	61		64	65
		Intermediate	29	36		39	40
		Valley	121	152		157	159
	Entire watershed		196	249		260	264
$V_{s,CD}$ $(10^3\ m^3)$	Reach	Mountain	119.0	145.0		147.3	148
		Intermediate	223.0	287.0		293.8	295.9
		Valley	477.0	534.0		540.4	542
	Entire watershed		819.0	966.0		986.0	990.4
LM	(m)		-14	-36	-79	-100	-93* -79**
A	$(10^3\ m^2)$		-9.8	-17.1	-28.7	-47.6	-38.1
EV	$(10^3\ m^3)$		-14	-24.5	-41	-68	-54.5
LCW	(m)		900	850	600	600	700

Note: LM = max linear movement, A = area of the beach, EV = evaluated volume, LCW = longshore changed width; *With/ **without rock breakwater barrier.

Table 4. Number of check dams (CD) and related retained sediment volumes ($V_{S,CD}$) for each torrent reach (Mr, Ir, Vr); morphological changes of shoreline near the mouth of the Gallico *fiumara* during (1954-1996) and after (1996-2020) the extended regulation campaign.

Time-window	**CD**				**$V_{s,CD}$** $(10^3\ m^3)$				**LM** (m)	**LCW** (m)	**A (-/+)**(a) $(10^3\ m^2)$	**EV (-/+)**(a) $(10^3\ m^2)$
	Mr	**Ir**	**Vr**	**All**	**Mr**	**Ir**	**Vr**	**All**				
1st programme **1954 - 1967**	46	29	121	196	119	223	477	819	-14	900	-9.8	-14.0
2nd programme **1967 - 1974**	15	7	31	53	26	64	57	147	-22	850	-7.3	-10.5
1974 - 1983(b)									-43	600	-11.6	-16.5
Integrative programme **1983 - 1996**	3	3	5	11	2.3	6.8	6.4	20	-21	600	-18.9	-14.5
After CD installation **1996 - 2020**	1	1	2	4	0.7	2.1	1.6	4.4	+7* **+21** **	700	9.5	+13.5
Entire period studied **1954 - 2020**	65	40	159	264	148	296	542	990.4	-93* **-79** **	650	-38.1	-42.0
Average values									-1.52 (m/yr)		-0.45 $(10^3\ m^2/yr)$	-0.83 $(10^3\ m^3/yr)$

Note: LM = max linear movement, A = area of the beach, EV = evaluated volume, LCW = longshore changed width; *With/ **without rock breakwater barrier; (a) - for "retreat", + for "accretion"; (b) the two time-frames depend on the available cartography.

POST-PRINT ONLY

3.4. Relationships between check dam system and shoreline change

The relationship has been expressed in terms of (i) LM of the shoreline with respect to CD installed in the watershed, and (ii) the eroded/increased sediment (EV) near the river mouth in relation to $V_{S,CD}$ (Fig. 8).

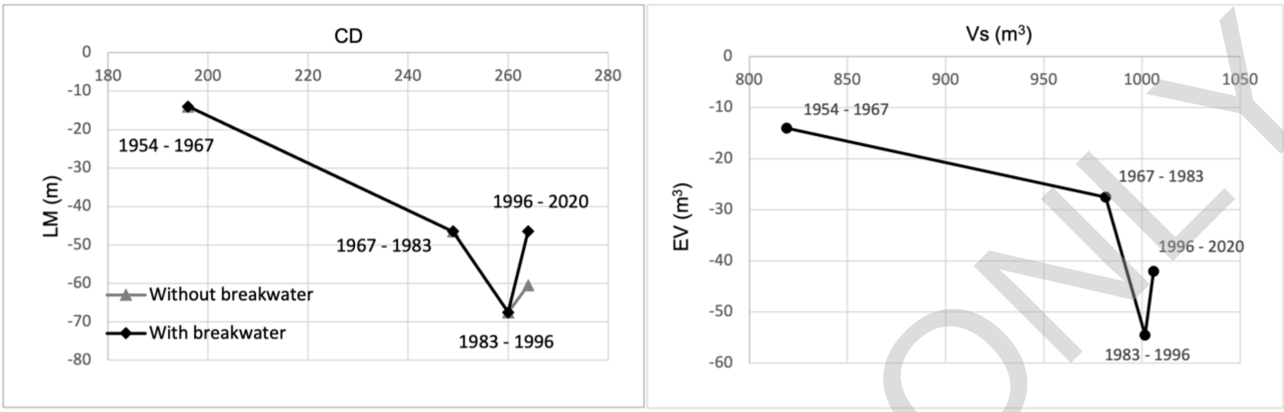


Fig. 8. Shoreline variation (LM, EV) depending on (a) number of check dams (CD) and (b) the sediment volumes retained by the check dam system ($V_{S,CD}$), in the time-windows 1954-1967, 1967-1983, 1983-1996 and 1996-2020.

The graphs show that during the three hydraulic regulation programmes (until 1996) the shoreline retreats for a total of about 55 m (Fig. 8a) with a lost EV of about 40 x 10^3 m^3 (Fig. 8b). From 1996 to the present (after the end of the campaigns) when the check dams are fully filled, both LM and EV are in countertrend. Even when simulating the absence of breakwaters, the tendency to move forward remains, although to a minor extent.

Moreover, the influence that the check dams installed in each torrent reach (CD_V, CD_I and CD_M) had on the (estimated) sediment volumes (EV) detracted/arriving at the river mouth is explained by the following equation:

$$v \cdot CD_V + i \cdot CD_I + m \cdot CD_M + b = EV \qquad (1)$$

where *m* (for Mr) is about 8.0127, *i* (for Ir) is -11.550, *v* (for Vr) is -14.469 and *b* (intercept) is 16.994. This analysis confirmed that the regulation of the Vr "weighs" more on the phenomenon investigated.

4. Discussion

The intensive regulation campaign conducted between 1955 and 1989 in Calabria has certainly contributed to mitigate the hydrogeological risk of the region. This was also achieved through the construction of several thousand check dams, most of which built in the valley reaches of the *fiumare*. The intensive regulation

POST-PRINT ONLY

programme, however, have altered the complex and delicate balance of the sediment flow from upstream to downstream which naturally fluctuates over time (Comiti, 2012; Dunne et al., 2003; Fryirs, 2013; Gomez et al., 2003; Liébault et al., 2005; Nakamura et al., 2000; Phillips et al., 2013) also depending on human interventions (Montgomery and Buffington, 1997; Piton et al., 2017). Check dams installed in the *fiumare* generally fill completely in a short time (2-3 years) after their construction; in the long term, by causing a change in the river bed slope, they modify the capacity of sediment transport favouring its deposition along the watercourse (Fig. 9) especially in the valley reaches where the natural slope (*ante-operam*) was already very low.

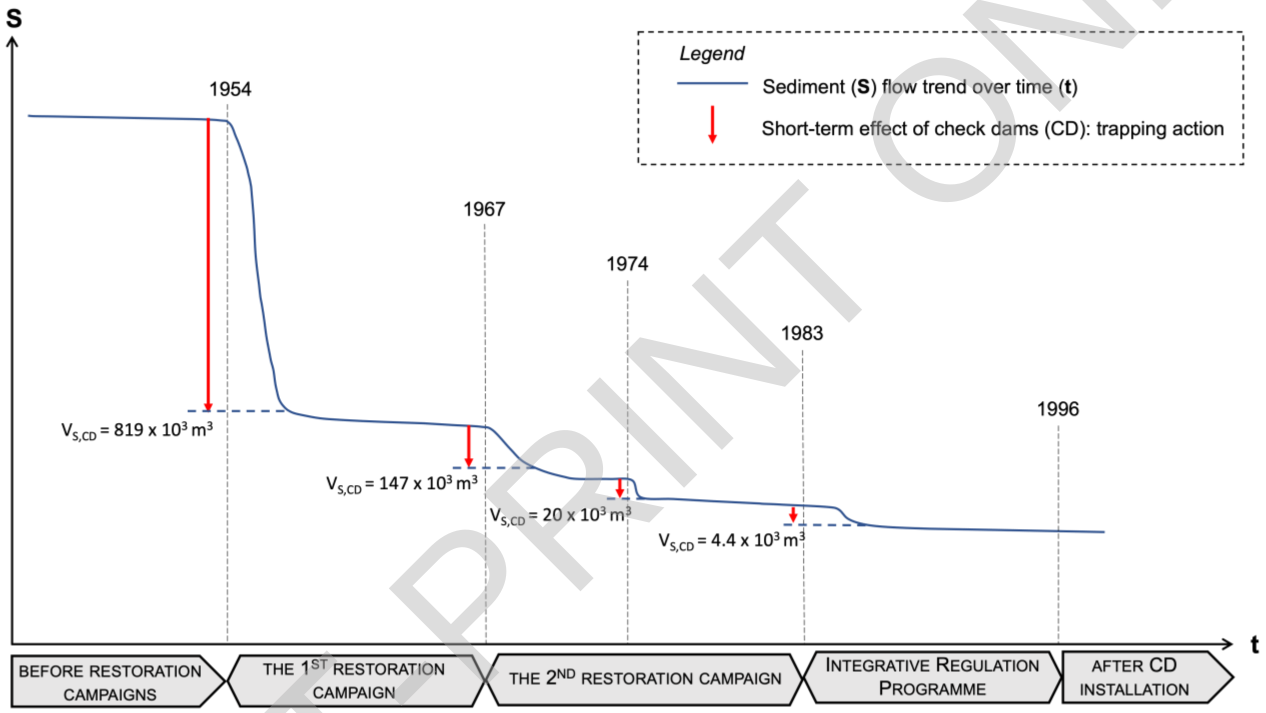


Fig. 9. Conceptual sketch representing the modified sediment flow trend over time due to the extensive land conservation operation, carried out through the construction of several thousands of check dams in Calabria. Rivers and streams play a key role within the sediment cascade by transferring and buffering fluxes between mountain reaches and areas and alluvial environments downstream. This activity is strongly related to (i) the rapid hydrological responses typical of upland environments, in conjunction with (ii) the sediment availability. Further specific investigation allowed us to demonstrate this phenomenon.

During an extreme flood event occurred in 2012, a sequence of 13 check dams installed in the lower part of the Gallico *fiumara* (up to about 5 km from the mouth) were destroyed: several hundred m^3 of sediment that was trapped behind the structures was mobilised and moved towards to the sea. The consequence was the advancement of the shoreline in the years immediately following the event (Fig. 10), and for a brief period

POST-PRINT ONLY

the sediments were temporary stabilised by the presence of breakwaters installed after the 1990s near the mouth (Fig. 11a). It should also be noted that, how reported in Table 5, only small variations in estimated volume (EV) were recorded in the 1996-2020 time-window: this is most probably due to the presence of the two thresholds installed right at the terminal section of the *fiumara* (Fig. 11b) whose purpose is to prevent further erosion of the beach once it reaches the sea. Furthermore, the destroyed check dams were rebuilt in a short time.

Fig. 10. Google satellite images of 2015 and 2020 of the mouth of the Gallico *fiumara.*

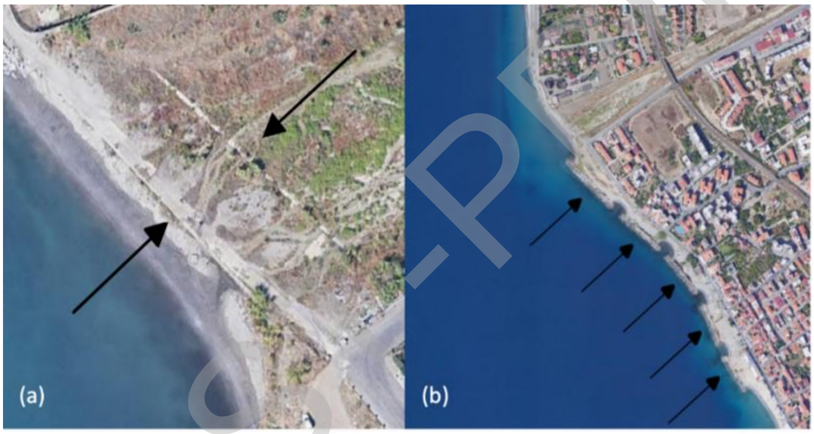


Fig. 11. Mouth of Gallico *fiumara*: view of the two thresholds (a) and the breakwater barriers (b).

Table 5 Sediment volumes retained by check dams ($V_{S,CD}$) installed in the valley reach (Vr) and variation over time of the estimated volume (EV, - reduction/+ accretion) of shoreline near the mouth of the Gallico watershed.

Total $V_{S,CD}$ (10^3 m^3)	**$V_{S,CD}$ in Vr** (10^3 m^3)	**EV** (10^3 m^3)		
1954 - 2020	**1954 - 2020**	**1954 – 2020**	**1954 – 1996**	**1996 – 2020**
990.4	542 **= 54.7 % of total $V_{S,CD}$**	-42.0	-55.5	+13.5

POST-PRINT ONLY

In 2015 a portion of the riverbed (about two kilometres from the mouth) was affected by an intervention to reduce the aggradation of the channel and mitigate the hydraulic risk. Therefore, approximately 56 x 10^3 m^3 of sediments were removed, and the hydraulic sections of the channel were recalibrated and restored. The effects of this intervention were monitored, and in 2020 a survey of the longitudinal profile of the riverbed was carried out to assess its evolutionary trend. Fig. 12 clearly shows that just five years later the recalibration the river bed has nearly reached its 2015 longitudinal profile, with a volume of redeposited sediment of about 40 x 10^3 m^3.

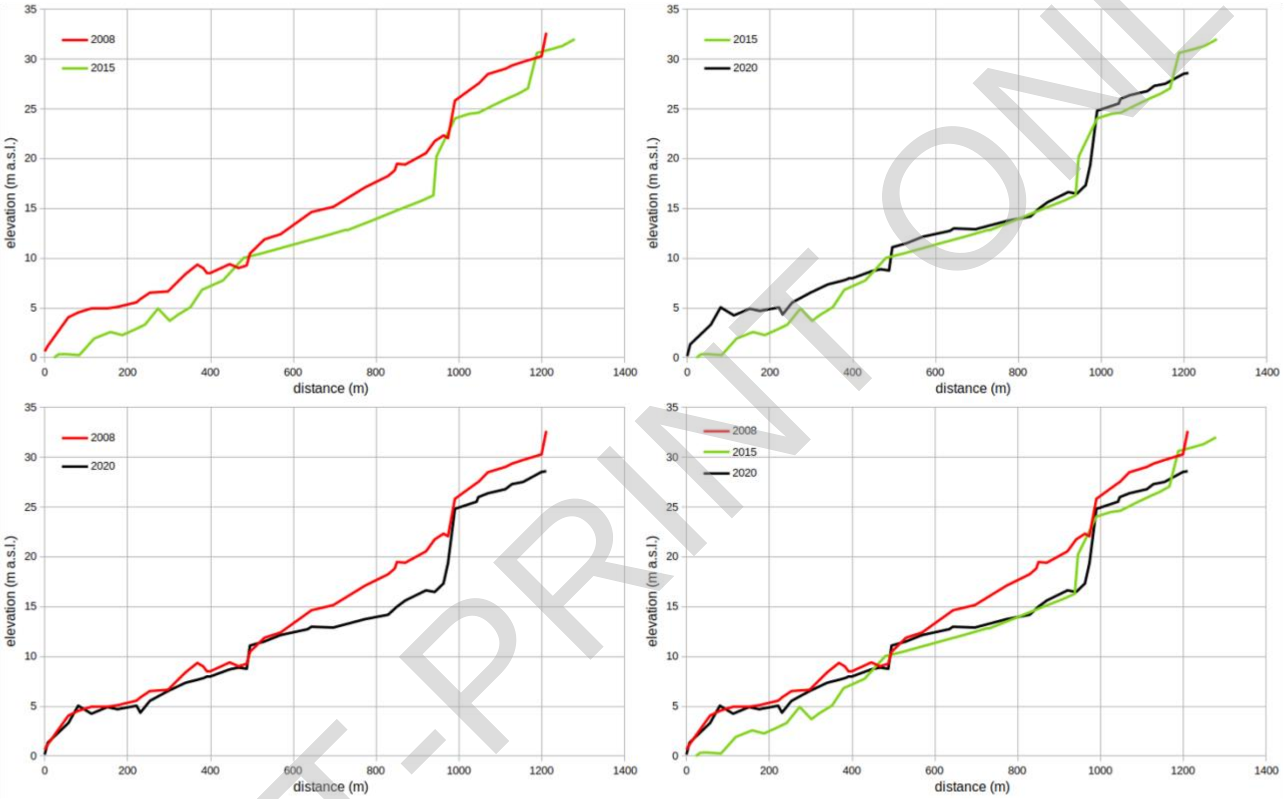


Fig. 12. Longitudinal profile before (2008), immediately after the recalibration (2015) and five years later (2020) in the terminal reach of Gallico *fiumara* (up to 1.3 km from the mouth) regulated with a sequence of check dams.

The influence of check dam system on coastline morphology is demonstrated by the cause-effect relationship between the large-scale hydraulic works programme and shoreline changes near the mouth: in fact after the two intensive hydraulic regulation campaigns (1954-1967, 1967-1983) the progressive increase in the number of check dams and, therefore, of the volumes retained by them, determined a drastic retreat of the shoreline. These two variables are strongly correlated with the change of the shoreline morphology expressed both in meters and in cubic meters, as clearly demonstrated.

POST-PRINT ONLY

The link is confirmed by what was observed from 1983 onwards, when the large-scale hydraulic works had ceased and only a few integrative interventions were carried out in the watershed. In this period, after the construction of breakwaters and thresholds installed near the mouth and, on the other hand, the collapse of the check dams in 2012, an advancement of the shoreline is recorded, albeit slight.

The check dams built in the final section of the river seem to have had a greater impact on the phenomenon. This is demonstrated not only by the linear regression (equation 1), but also by the tendency of the river bed to deposit large sediment volumes where they were removed with the recalibration intervention in 2015.

5. Conclusion

The work does not fully explain the processes that regulate the dynamics of the shoreline and thus of the watershed-coastal continuum, as well as the long-term effect of the check dams; the effects of sea storms that reach significant maximum wave heights on the order of only a couple of meters have not been investigated either: these modest values are caused by the morphological peculiarity of the territory, which is located within the Strait of Messina where the fetches have an extension of the order of just tens of km. However, the paper clearly demonstrates how it is possible to attribute to downstream check dam systems a negative effect on coastal erosion, which also determines an increase in hydraulic risk in more intensely urbanised areas. While structures in the mountain reaches are essential to control sediment transport phenomena, those in lower reach, on the other hand, would appear to be somewhat questionable, given that the slopes in the valleys of the *fiumare* are already very low, and the installation of check dams only contributes to the sedimentation of material which would otherwise reach the sea.

In the light of the results obtained, therefore, it would be useful to promote a more in-depth debate on the role of check dams in river contexts such as those of *fiumara*. Here, especially in the lower reach, the marked presence of these structures is often contradictory both with the natural evolution of the watercourse and with the function that the works should play.

Generally speaking, it would be necessary to evaluate the opportunity to reconvert these works or, in the most problematic situations, to demolish them. Consequently, the approach described in the paper can be the basis of a new vision of planning and management of coastal areas, that considering the processes of the entire watershed-coast system and favouring rebalancing measures of the sedimentary processes at the mouth (e.g., the removal of surplus check dams from the downstream parts of the river) with respect to the construction of new rigid coastal defence interventions.

POST-PRINT ONLY

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6. References

Abbasi, N.A., Xu, X., Lucas-Borja, M.E., Dang, W., Liu, B., 2019. The use of check dams in watershed management projects: Examples from around the world. Sci. Total Environ. 676, 683–691.

Acciarri, A., Bisci, C., Cantalamessa, G., Di Pancrazio, G., 2016. Anthropogenic influence on recent evolution of shorelines between the Conero Mt. and the Tronto R. mouth (southern Marche, Central Italy). CATENA 147, 545–555. https://doi.org/10.1016/j.catena.2016.08.018

Acerbo, G., 1937. La bonifica integrale e la sistemazione montana. Roma, Italy.

Aceto, L., Caloiero, T., Pasqua, A.A., Petrucci, O., 2016. Analysis of damaging hydrogeological events in a Mediterranean region (Calabria). J. Hydrol. 541, 510–522. https://doi.org/10.1016/j.jhydrol.2015.12.041

A.FO.R., (Agenzia Forestale Regione Calabria), 1998. Attività di ricerca inerenti le opere di sistemazione idraulico-forestali e la formazione del relativo catasto. Istituto Genio Rurale, Università degli Studi di Reggio Calabria.

Aiello, A., Canora, F., Pasquariello, G., Spilotro, G., 2013. Shoreline variations and coastal dynamics: A space–time data analysis of the Jonian littoral, Italy. Estuar Coast Shelf S 129, 124–135. https://doi.org/10.1016/j.ecss.2013.06.012

Anthony, E.J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., Nguyen, V.L., 2015. Linking rapid erosion of the Mekong River delta to human activities. Sci. Rep. 5, 1–12.

Anthony, E.J., Marriner, N., Morhange, C., 2014. Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: From progradation to destruction phase? Earth-Sci. Rev. 139, 336–361.

Antronico, L., Petrucci, O., Scalzo, A., Sorriso-Valvo, M., 1998. Relationships between land degradation forms and historical development of malaria in Calabria (Southern Italy). Int. J. Anthropol. 13, 211–217. https://doi.org/10.1007/BF02452668

Ballesteros-Canovas, J.A., Bombino, G., D'Agostino, D., Denisi, P., Labate, A., Stoffel, M., Zema, D.A., Zimbone, S.M., 2020. Tree-ring based, regional-scale reconstruction of flash floods in Mediterranean mountain torrents. CATENA 189, 104481. https://doi.org/10.1016/j.catena.2020.104481

Barbaro, G., Bombino, G., Foti, G., Borrello, M.M., Puntorieri, P., 2019. Shoreline evolution near river mouth:

POST-PRINT ONLY

Case study of Petrace River (Calabria, Italy). Reg. Stud. Mar. Sci. 29, 100619. https://doi.org/10.1016/j.rsma.2019.100619

Batalla, R.J., 2003. Déficit de sedimento fluvial a causa de las presas y las extracciones de áridos. Revisión con ejemplos del NE de España.

Bevilacqua, P., 1987. La bonifica nel Mezzogiorno d’Italia: alcune considerazioni. Riv. Storia Dell’Agricoltura Accad. Econ.-Agrar. Dei Georgofili.

Boak, E.H., Turner, I.L., 2005. Shoreline definition and detection: a review. Journal of Coastal Research, 21(4), 688–703. https://doi.org/10.2112/03-0071.1

Boix-Fayos, C., Barberá, G.G., López-Bermúdez, F., Castillo, V.M., 2007. Effects of check dams, reforestation and land-use changes on river channel morphology: Case study of the Rogativa catchment (Murcia, Spain). Geomorphology 91, 103–123. https://doi.org/10.1016/j.geomorph.2007.02.003

Bombino, G., 2020. A (new) suggestive hypothesis about the origin of the term fiumara (seasonally-flowing and high hazard streams of Southern Italy). Mediterr. Chron. 10, 163–173.

Bombino, G., 2009. Interaction between vegetation and flow for restoration of channalized fiumaras in urban contexts.

Bombino, G., Barbaro, G., D’Agostino, D., Denisi, P., Labate, A., Zimbone, S.M., 2022. A method for estimating stored sediment volumes by check dam systems at the watershed level: example of an application in a Mediterranean environment. J. Soils Sediments 22, 1329–1343. https://doi.org/10.1007/s11368-022-03163-6

Bombino, G., Gurnell, A.M., Tamburino, V., Zema, D.A., Zimbone, S.M., 2009. Adjustments in channel form, sediment calibre and vegetation around check-dams in the headwater reaches of mountain torrents, Calabria, Italy. Earth Surf. Process. Landf. 1011–1021. https://doi.org/10.1002/esp.1791

Bombino, G., Gurnell, A.M., Tamburino, V., Zema, D.A., Zimbone, S.M., 2007. A method for assessing channelization effects on riparian vegetation in a Mediterranean environment. River Res. Appl. 23, 613–630. https://doi.org/10.1002/rra.1004

Bombino, G., Tamburino, V., Zimbone, S.M., 2006. Assessment of the effects of check-dams on riparian vegetation in the Mediterranean environment: A methodological approach and example application. Ecol. Eng. 27, 134–144. https://doi.org/10.1016/j.ecoleng.2006.01.005

Caloiero, T., Coscarelli, R., Ferrari, E., 2008. Trend analysis of short rainfalls annual maxima in Calabria. Bios, Cosenza (Italy), pp. 103–111.

Castillo Sanchez, V.M., Mosch, W.M., García, C.C., Barberá, G.G., Cano, J.A.N., López-Bermúdez, F.,

POST-PRINT ONLY

2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). CATENA 70, 416–427. https://doi.org/10.1016/j.catena.2006.11.009

Castillo, V.M., Mosch, W.M., García, C.C., Barberá, G.G., Cano, J.A.N., López-Bermúdez, F., 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). CATENA 70, 416–427. https://doi.org/10.1016/j.catena.2006.11.009

Catella, M., Paris, E., Solari, L., 2005. Case Study: Efficiency of Slit-Check Dams in the Mountain Region of Versilia Basin. J. Hydraul. Eng. 131, 145–152. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:3(145)

Coltori, M., 1997. Human impact in the Holocene fluvial and coastal evolution of the Marche region, Central Italy. CATENA 30, 311–335. https://doi.org/10.1016/S0341-8162(97)00007-6

Comiti, F., 2012. How natural are Alpine mountain rivers? Evidence from the Italian Alps: HOW NATURAL ARE MOUNTAIN RIVERS OF THE ITALIAN ALPS? Earth Surf. Process. Landf. 37, 693–707. https://doi.org/10.1002/esp.2267

Conesa García, C., 2004. Los diques de retencion en cuencas de régimen torrencial: diseño, tipos y funciones 18.

Conesa-García, C., López-Bermúdez, F., García-Lorenzo, R., 2007. Bed stability variations after check dam construction in torrential channels (South-East Spain). Earth Surf. Process. Landf. 32, 2165–2184. https://doi.org/10.1002/esp.1521

Dean, R.G., 2002. Beach nourishment: theory and practice. World scientific.

Del Río, L., Gracia, F.J., 2013. Error determination in the photogrammetric assessment of shoreline changes. Nat. Hazards 65, 2385–2397.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in a mountainous terrain.

Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature 340, 215–217. https://doi.org/10.1038/340215a0

D'Ippolito, A., Ferrari, E., Iovino, F., Nicolaci, A., Veltri, A., 2013. Reforestation and land use change in a drainage basin of southern Italy. IForest - Biogeosciences For. 6, 175–182. https://doi.org/10.3832/ifor0741-006

Dunne, J.A., Harte, J., Taylor, K.J., 2003. Subalpine meadow flowering phenology responses to climate change: integrating experimental and gradient methods. Ecol. Monogr. 73, 69–86. https://doi.org/10.1890/0012-9615(2003)073[0069:SMFPRT]2.0.CO;2

POST-PRINT ONLY

Fairbridge, R.H., 1968. The Encyclopedia of Geomorphology. Reinhold Book Corp., N.Y.

Falqués, A., 2006. Wave driven alongshore sediment transport and stability of the Dutch coastline. Coast. Eng., Coastal Hydrodynamics and Morphodynamics 53, 243–254. https://doi.org/10.1016/j.coastaleng.2005.10.012

Foti, G., Barbaro, G., Barillà, G.C., Frega, F., 2022a. Effects of Anthropogenic Pressures on Dune Systems—Case Study: Calabria (Italy). J. Mar. Sci. Eng. 10, 10.

Foti, G., Barbaro, G., Barillà, G.C., Mancuso, P., Puntorieri, P., 2022b. Shoreline evolutionary trends along Calabrian coasts. Causes and classification. Front. Mar. Sci. https://doi.org/10.3389/fmars.2022.846914

Foti, G., Barbaro, G., Bombino, G., Fiamma, V., Puntorieri, P., Minniti, F., Pezzimenti, C., 2019. Shoreline changes near river mouth: case study of Sant'Agata River (Reggio Calabria, Italy). Eur. J. Remote Sens. 52, 102–112. https://doi.org/10.1080/22797254.2019.1686955

Fryirs, K., 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landf. 38, 30–46. https://doi.org/10.1002/esp.3242

Gilbert, G.K., 1914. The transportation of debris by running water (No. 86). US Government Printing Office.

Gilbert, G.K., 1887. Report of the geology of the Henry Mountains, Utah. US Geog. and Geo. survey of the rocky mountain region.

Gomez, B., Banbury, K., Marden, M., Trustrum, N.A., Peacock, D.H., Hoskin, P.J., 2003. Gully erosion and sediment production: Te Weraroa Stream, New Zealand: GULLY EROSION, SEDIMENT PRODUCTION, AND STORAGE. Water Resour. Res. 39. https://doi.org/10.1029/2002WR001342

Gomi, T., Sidle, R.C., Woodsmith, R.D., Bryant, M.D., 2003. Characteristics of channel steps and reach morphology in headwater streams, southeast Alaska. Geomorphology 51, 225–242. https://doi.org/10.1016/S0169-555X(02)00338-0

Heede, B.H., 1986. Designing for dynamic equilibrium in streams. JAWRA J. Am. Water Resour. Assoc. 22, 351–357.

Heede, B.H., 1967. Gully Development and Control in the Rocky Moun- tain of Colorado. Colorado State University: Fort Collins, CO. (Doctoral thesis). Colorado State University.

Helley, E.J., LaMarche, V.C., 1973. Historic flood information for northern California streams from geological and botanical evidence; vegetation and hydrologic phenomena. Geol Surv Prof Pap US Dep Inter.

Kellerhals, R., Bray, D.I., Church, M., 1976. Classification and Analysis of River Processes 813–829.

Kondolf, G.M., 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. Environ. Manage. 21, 533–551. https://doi.org/10.1007/s002679900048

POST-PRINT ONLY

Kondolf, G.M., 1995. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. Aquat. Conserv. Mar. Freshw. Ecosyst. 127–141.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Kuleli, T., 2010a. Quantitative analysis of shoreline changes at the Mediterranean Coast in Turkey. Environ. Monit. Assess. 167, 387–397. https://doi.org/10.1007/s10661-009-1057-8

Kuleli, T., 2010b. Quantitative analysis of shoreline changes at the Mediterranean Coast in Turkey. Environ. Monit. Assess. 167, 387–397. https://doi.org/10.1007/s10661-009-1057-8

Lane, E.W., 1955. Importance of fluvial morphology in hydraulic engineering. Proc. Am. Soc. Civ. Eng. 81.

Leeder, M.L., 1999. Sedimentary environments and sedimentation: From turbulence to tectonics.

Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications (Vol. 252). US Government Printing Office.

Liébault, F., Gomez, B., Page, M., Marden, M., Peacock, D., Richard, D., Trotter, C.M., 2005. Land-use change, sediment production and channel response in upland regions. River Res. Appl. 21, 739–756. https://doi.org/10.1002/rra.880

Limber, P.W., Patsch, K.B., Griggs, G.B., 2008. Coastal sediment budgets and the littoral cutoff diameter: a grain size threshold for quantifying active sediment inputs. J. Coast. Res. 122–133.

Martínez del Pozo, J., Anfuso, G., 2008. Spatial approach to medium-term coastal evolution in south Sicily (Italy): implications for coastal erosion management. J. Coast. Res. 24, 33–42.

Medici, G., 1954. I consorzi di bonifica e i loro attuali problemi. Roma, Italy.

Miao, C., Ni, J., Borthwick, A.G.L., 2010. Recent changes of water discharge and sediment load in the Yellow River basin, China. Prog. Phys. Geogr. Earth Environ. 34, 541–561. https://doi.org/10.1177/0309133310369434

Montgomery, D.R., Buffington, J.M., 1998. Channel Processes, Classification and Response. River Ecol. Manag. 112, 1250–1263.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 596–611.

Moore, L.J., 2000. Shoreline Mapping Techniques 15.

Morton, R.A., 2008. National assessment of shoreline change: Part 1: Historical shoreline changes and associated coastal land loss along the US Gulf of Mexico. Diane Publishing.

Nakamura, F., Swanson, F.J., Wondzell, S.M., 2000. Disturbance regimes of stream and riparian systems —

POST-PRINT ONLY

a disturbance-cascade perspective. Hydrol Process 12.

Petrucci, O., Pasqua, A.A., 2013. Rainfall-Related Phenomena Along a Road Sector in Calabria (Southern Italy), in: Margottini, C., Canuti, P., Sassa, K. (Eds.), Landslide Science and Practice. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 145–151. https://doi.org/10.1007/978-3-642-31313-4_19

Petrucci, O., Pasqua, A.A., 2012. Damaging events along roads during bad weather periods: a case study in Calabria (Italy). Nat. Hazards Earth Syst. Sci. 12, 365–378. https://doi.org/10.5194/nhess-12-365-2012

Petrucci, O., Polemio, M., 2007. Flood risk mitigation and anthropogenic modifications of a coastal plain in southern Italy: combined effects over the past 150 years. Nat. Hazards Earth Syst. Sci. 7, 361–373. https://doi.org/10.5194/nhess-7-361-2007

Phillips, C.J., Rey, F., Marden, M., Liébault, F., 2013. Revegetation of steeplands in France and New Zealand: geomorphic and policy responses. N. Z. J. For. Sci. 43, 14. https://doi.org/10.1186/1179-5395-43-14

Pilkey, O.H., Dixon, K., 1996. The Corps and the Shore., Island Press. ed. Washington, D.C.

Piton, G., Carladous, S., Recking, A., Tacnet, J.M., Liébault, F., Kuss, D., Queffeléan, Y., Marco, O., 2017. Why do we build check dams in Alpine streams? An historical perspective from the French experience: A Review of the Subtle Knowledge of 19th Century Torrent-Control-Engineers. Earth Surf. Process. Landf. 42, 91–108. https://doi.org/10.1002/esp.3967

Piton, G., Recking, A., 2016. Design of Sediment Traps with Open Check Dams. I: Hydraulic and Deposition Processes. J. Hydraul. Eng. 142, 04015045. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001048

Poulos, S.E., Chronis, G.T., Collins, M.B., Lykousis, V., 2000. Thermaikos Gulf coastal system, NW Aegean Sea: an overview of water/sediment fluxes in relation to air–land–ocean interactions and human activities. J. Mar. Syst. 25, 47–76.

Powell, J.W., 1875. Exploration of the Colorado River of the West and Its Tributaries: Explored in 1869, 1870, 1871, and 1872, Under the Direction of the Secretary of the Smithsonian Institution. US government printing office.

Quiñonero-Rubio, J.M., Nadeu, E., Boix-Fayos, C., Vente, J. de, 2016. Evaluation of the Effectiveness of Forest Restoration and Check-Dams to Reduce Catchment Sediment Yield. Land Degrad. Dev. 27, 1018–1031. https://doi.org/10.1002/ldr.2331

Ramos-Diez, I., Navarro-Hevia, J., Fernández, R.S.M., Díaz-Gutiérrez, V., Mongil-Manso, J., 2016. Geometric models for measuring sediment wedge volume in retention check dams. Water Environ. J. 30, 119–127. https://doi.org/10.1111/wej.12165

POST-PRINT ONLY

Romero-Díaz, A., 2008. Los diques de corrección hidrológica como instrumentos de cuantificación de la erosión. Cuad. Investig. Geográfica 34, 83. https://doi.org/10.18172/cig.1208

Rosskopf, C.M., Di Paola, G., Atkinson, D.E., Rodríguez, G., Walker, I.J., 2018a. Recent shoreline evolution and beach erosion along the central Adriatic coast of Italy: the case of Molise region. J. Coast. Conserv. 22, 879–895. https://doi.org/10.1007/s11852-017-0550-4

Rosskopf, C.M., Di Paola, G., Atkinson, D.E., Rodríguez, G., Walker, I.J., 2018b. Recent shoreline evolution and beach erosion along the central Adriatic coast of Italy: the case of Molise region. J. Coast. Conserv. 22, 879–895. https://doi.org/10.1007/s11852-017-0550-4

Ruini, M., 1913. Prima relazione sull’applicazione delle leggi speciali dal 30 giugno 1906 al 30 giugno 1913, Le opere pubbliche in Calabria. Istituto Italiano di Arti Grafiche, Bergamo.

Sabato, L., Tropeano, M., 2004. Fiumara: A kind of high hazard river. Phys Che Earth 9.

Sannino, G., Carillo, A., Pisacane, G., Naranjo, C., 2015. On the relevance of tidal forcing in modelling the Mediterranean thermohaline circulation. Prog. Oceanogr. 134, 304–329.

Schumm, S.A., 1977. The Fluvial System 338.

Serrato, F.B., Díaz, A.R., 2005. EROSIÓN EN CAUCES AFECTADOS POR OBRAS DE CORRECCIÓN HIDROLÓGICA (CUENCA DEL RÍO QUÍPAR, MURCIA). Papeles Geogr. 14.

Sorriso-Valvo, M., Bryan, R.B., Yair, A., Iovino, F., Antronico, L., 1995. Impact of afforestation on hydrological response and sediment production in a small Calabrian catchment. CATENA 25, 89–104. https://doi.org/10.1016/0341-8162(95)00002-A

Stanley, D.J., Warne, A.G., 1998. Nile Delta in its destruction phase. J. Coast. Res. 795–825.

Tsimplis, M.N., Baker, T.F., 2000. Sea level drop in the Mediterranean Sea: an indicator of deep water salinity and temperature changes? Geophys. Res. Lett. 27, 1731–1734.

Tsimplis, M.N., Woolf, D.K., Osborn, T.J., Wakelin, S., Wolf, J., Flather, R., Shaw, A.G.P., Woodworth, P., Challenor, P., Blackman, D., 2005. Towards a vulnerability assessment of the UK and northern European coasts: the role of regional climate variability. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 363, 1329–1358.

Velegrakis, A.F., Vousdoukas, M.I., Andreadis, O., Adamakis, G., Pasakalidou, E., Meligonitis, R., Kokolatos, G., 2008. Influence of dams on downstream beaches: Eressos, Lesbos, Eastern Mediterranean. Mar. Georesources Geotechnol. 26, 350–371.

Viparelli, M., 1972. La sistemazione delle aste terminali delle fiumare calabre. 276.

Vousdoukas, M.I., Velegrakis, A.F., Plomaritis, T.A., 2007. Beachrock occurrence, characteristics, formation mechanisms and impacts. Earth-Sci. Rev. 85, 23–46.

POST-PRINT ONLY

Wang, X., Liu, T., Yang, W., 2012. Development of a robust runoff-prediction model by fusing the Rational Equation and a modified SCS-CN method. Hydrol. Sci. J. 57, 1118–1140. https://doi.org/10.1080/02626667.2012.701305

Warrick, J.A., 2020. Littoral sediment from rivers: Patterns, rates and processes of river mouth morphodynamics. Front. Earth Sci. 8, 355.

Williams, G.P., 1978. Bank-full discharge of rivers. Water Resour. Res. 14, 1141–1154. https://doi.org/10.1029/WR014i006p01141

Willis, C.M., Griggs, G.B., 2003. Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability. J. Geol. 111, 167–182.

Xu, J., 2005. Temporal variation of river flow renewability in the middle Yellow River and the influencing factors. Hydrol. Process. 19, 1871–1882. https://doi.org/10.1002/hyp.5652

Yazdi, J., Sabbaghian Moghaddam, M., Saghafian, B., 2018. Optimal Design of Check Dams in Mountainous Watersheds for Flood Mitigation. Water Resour. Manag. 32, 4793–4811. https://doi.org/10.1007/s11269-018-2084-4

Zhao, G., Kondolf, G.M., Mu, X., Han, M., He, Z., Rubin, Z., Wang, F., Gao, P., Sun, W., 2017. Sediment yield reduction associated with land use changes and check dams in a catchment of the Loess Plateau, China. Catena 148, 126–137.

POST-PRINT ONLY