RESEARCH PAPER

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GEOMORPHOLOGY AND SEDIMENTOLOGY OF EPHEMERAL STREAMS OF CALABRIA, SOUTHERN ITALY

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ABSTRACT. In southern Italy, especially in Calabria, rivers are dry for most of the time, but intense rainfalls may turn them into roaring monsters, causing devastating floods. These rivers, locally known as *"fiumaras"*, are poorly studied though they play an important role in landscape shaping and pose serious threats to the local infrastructures and urban settlements. Basic catchment and channel geomorphic data of several rivers were collected from the literature and in the field. A comparison is made with river catchments of similar size in more humid environments to demonstrate that local physiography, watershed geomorphology, and channel characteristics may exacerbate the risk of flooding. The sedimentology of the study rivers is investigated to verify if fiumaras have specific bedform associations or stratigraphic arrangements that can be used to interpret ancient sandstones and conglomerates as deposited in an active tectonic setting under the Mediterranean climate. Four representative rivers were selected for investigation on the alluvium architecture, and field campaigns were carried out to collect bed material samples and to identify the occurrence of coarse and fine-grained bedforms. The fiumaras have a braided morphology, but the longitudinal bars do not have a fine tail and result from dissection processes rather than large bedform deposition and downstream migration. The braid bar characteristics, the poor internal organization of the tabular beds, and the occurrence of the largest boulders on top of the bars indicate the prevalence of high deposition rates from hyperconcentrated flows.

KEYWORDS: ephemeral stream, fiumara, braided river, alluvium, hyperconcentrated flow, Calabria

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INTRODUCTION

In Calabria, southern Italy, ephemeral or intermittent rivers are common (Sabato and Tropeano 2004). These rivers are dry for most of the time, and water flow is resumed only in response to high-intensity rainfalls. Their channels are short, coarse-grained, and steep, even in the most downstream reaches. In recent decades, several flash floods devastated infrastructures and urban settlements with negative repercussions on the economic development of the region. This kind of river system is known by the local name of *"fiumara",* a word used all over Italy to indicate an ephemeral river with high and unpredictable discharge variability that changes from a dry bed into a roaring monster in minutes. In this paper, we decided to use the local name in its original form for clarity and cultural accuracy.

Fiumaras play an important role in shaping the landscape of the Calabria region. With their steep channels and very energetic flood flows, commonly associated with the mobilization of large quantities of coarse-grained bedload material, these ephemeral/intermittent rivers have strong impacts on several human activities, including agriculture, pastoralism, and the tourism industry, to name the most important. However, the hydrological, hydraulic, and geomorphological characteristics of these rivers have been the subject of only a handful of studies. Most previous research investigated the flash flood hazard associated with the fiumaras in Calabria using hydrological models (Ferrari et al. 1988; Versace et al. 1989 and 2017; Sabato and Tropeano 2004). Though fiumaras are ubiquitous in Calabria, flow data is scarce since only a few larger rivers are monitored in this region. Usually, the existing flow gauges are located in the mountain reaches and cover only a small portion of the catchment. Moreover, the available time series are short and discontinuous and do not allow for investigating the fiumaras' flood hydrographs, hydrology, and hydraulic characteristics. Other studies were focused on hydraulic issues such as the dominant discharge (Ferro and Porto 2012), the shear stress critical conditions for streambed particle entrainment (Porto and Gessler, 1990; Ferro and Porto 2011) or the sediment yield (Foti et al. 2022) using the empirical model of Gavrilovic (1972).

More of the same paucity of studies was encountered looking for investigations on the fluvial geomorphology and processes of the Calabrian fiumaras, with just a few exceptions of publications reporting about very basic geomorphic data (Billi and Biamonte, 1995; Versace et al. 2017). The fiumaras are a peculiar kind of ephemeral stream and, like their counterparts in more arid lands, lay down a thick alluvium of coarse-grained material whose sedimentological characteristics are poorly known. The understanding of the fiumaras depositional processes and features can contribute to recognizing old conglomerate and sandstone as deposited in arid and semi-arid environments and to assess their potential as reservoirs of hydrocarbon and ore deposits. While the sedimentology and bedforms of ephemeral, sand bed rivers are rather well documented (Williams 1971; Picard and High 1973; Shepherd 1987; Abdullatif 1989), much poorer information is available for gravel-bed, ephemeral streams (Dunkerley 1992; Hassan 2005; Laronne and Shlomi 2007; Billi 2008; Billi 2016). The fiumaras, though they may share some sedimentological characteristics with dryland rivers in other parts of the world, typically form under specific geotectonic and climate conditions. Their hydrology and morphological processes make them a peculiar kind of ephemeral stream within the Mediterranean area that, unfortunately, received very little attention from scientists (Sabato 1989), notwithstanding their relevance in landscape shaping.

Given the unavailability of flow data time series and aiming at reducing the gap of information on the geomorphology and sedimentology of the Calabrian fiumaras, this study was designed to pursue the following main goals:

1) to investigate the catchment morphology of selected fiumaras in Calabria to verify if their peculiar characteristics may contribute to exacerbating the hazard of devastating flash floods, often accompanied by high sediment supply and depositional rates in the coastal plain belt;

2) to investigate the main sedimentological characteristics of the Calabria fiumaras to verify, also through the comparison with ephemeral streams in different arid and semiarid environments, if their depositional structures, bedding arrangements, and bedforms are specific to this kind of river and if they can be used as diagnostic elements to interpret the depositional environment of ancient sandstone and conglomerate laid down by rivers like the fiumaras, found in an active tectonic setting and Mediterranean climate.

STUDY AREA

Calabria is a long and narrow, arch-shaped southwestern sub-peninsula of southern Italy (Fig. 1). It has a mountainous spine originated by thrust fault tectonics that emplaced the Calabrian orogen, consisting of basement rocks (granitoids, gneisses and shists), to become part of the southern Apennines. The Calabria arch is a fragment of the Alpine chain that, in the Miocene, was detached from the Sardinia-Corsica block and migrated to the present position (Cirrincione et al., 2015). Pleistocene terraced marine deposits at 1300 m asl witness a fast uplifting of the region through extensional tectonics. The highest mountain peaks range from 1100 to 2200 m asl. The result of such complex and intense geodynamics is a mountain range, taking up most of the region, interrupted by tectonic depressions and surrounded by narrow coastal plains; though, in some places, the mountain slopes may almost reach the sea. In such a physiography, most of the rivers are short and steep. Most rivers are ephemeral, with a wide range of discharge between the dry bed condition in the summer and high devastating flood flows in autumn or winter, except for a few (three or four) larger rivers that have a sustained base flow year-round.

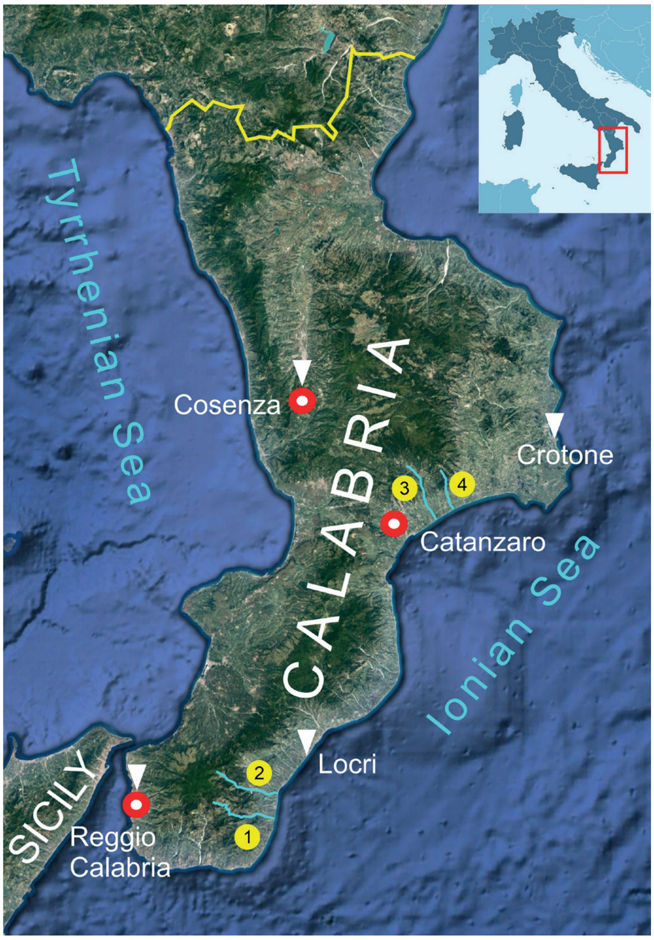

Fig. 1. Location map of the Calabria Region. The white triangles indicate the meteorological stations used in this study to characterize the climate of the region. The circled numbers indicate the four rivers investigated in the field: 1 = La Verde R.; 2= Bonamico R.; 3 = Simeri R.; 4 = Scilotraco R

The region is subjected to a typical Mediterranean climate (*Csa* according to the Koppen climate classification) characterized by high temperatures in the summer and the lowest monthly temperature less than 18°C but higher than -3°C (Fig. 2). Precipitation is mainly concentrated in the autumn and winter months, though some small differences are observed between the Tyrrhenian and the Ionian sides (Fig. 2). Annual precipitation and the number of rainy days range from 500 to over 2000 mm and from 60 to more than 120 days, respectively, on the eastern coast to the most elevated areas around the highest mountain peaks. The high mountain areas record the highest daily rainfall intensities of 175-200 mm (with peaks of 360–630 mm, Versace et al., 2017), whereas the southwestern coast records the lower values. Average rainfall intensities in three and one hour vary from 30-45 mm in the central northern portion to 65-75 mm in the southern mountain peaks and from 20 to 50 mm, respectively. Such high-intensity values are expected to be exceeded during extreme events (92 and 160 mm in three and one hours, respectively) and capable of generating high, devastating floods (6-20 $m^3 s^{-1} km^{-2}$ – Versace et al, 2017), during which peak flow may be as much as three to four orders of magnitude higher than mean annual discharge (in semi-perennial rivers) (Fig. 2) These climate data are based on ECMWF (European Centre for Medium-Range Weather Forecasts) data, collected between 1991 and 2021.

The monthly flow variation of a couple of fiumaras, taken as an example, is reported in Fig. 3. The flow gauges considered are in the headwaters of the respective catchments and take up only a very small portion of the watershed. The pattern of monthly mean discharge follows the typical Mediterranean distribution of monthly rainfall, with low flows in the summer and higher discharges in the autumn and winter months. In the Alli river, the recharge of the autumn rain is not enough to resume an appreciable discharge to sustain the freshwater biota, which is reached only after the December and January rains (see Fig. 3). The flow data used in Fig. 3 were obtained from the Annali Idrologici of the National Hydrological Service (Servizio Idrografico, 1916-1998) and cover the intervals 1925-1930, 1932-1942 and 1947-1979 for the Alli River and the interval 1964-1978 for the Trionto River. These data are not updated or uniform, but they can show the general river flow pattern typical of the Mediterranean environment.

DATA SOURCES AND METHODS

This study utilized two datasets. The first one, identified as Dataset 1, is based on the data of Biamonte (1993) and Billi and Biamonte (1995). The second dataset, Dataset 2, is based on data published by the University of Calabria and the Calabria Region Civil Protection (Versace et al., 2017). The data was split into two subsets because the data is not homogeneous for the rivers considered, their number, and the parameters measured (Table 1, 2). Dataset 1 was expanded by including the streambed gradient of the terminal reaches, that is, the downstream portion of the channels crossing the coastal plain from the exit of the mountainous portion of the catchment to the outlet into the Ionian or the Tyrrhenian seas. The streambed gradient of the terminal reaches was obtained from measurement by the ruler tool on Google Earth aerial images. More detailed information about this methodology can be found in Billi et al. (2018).

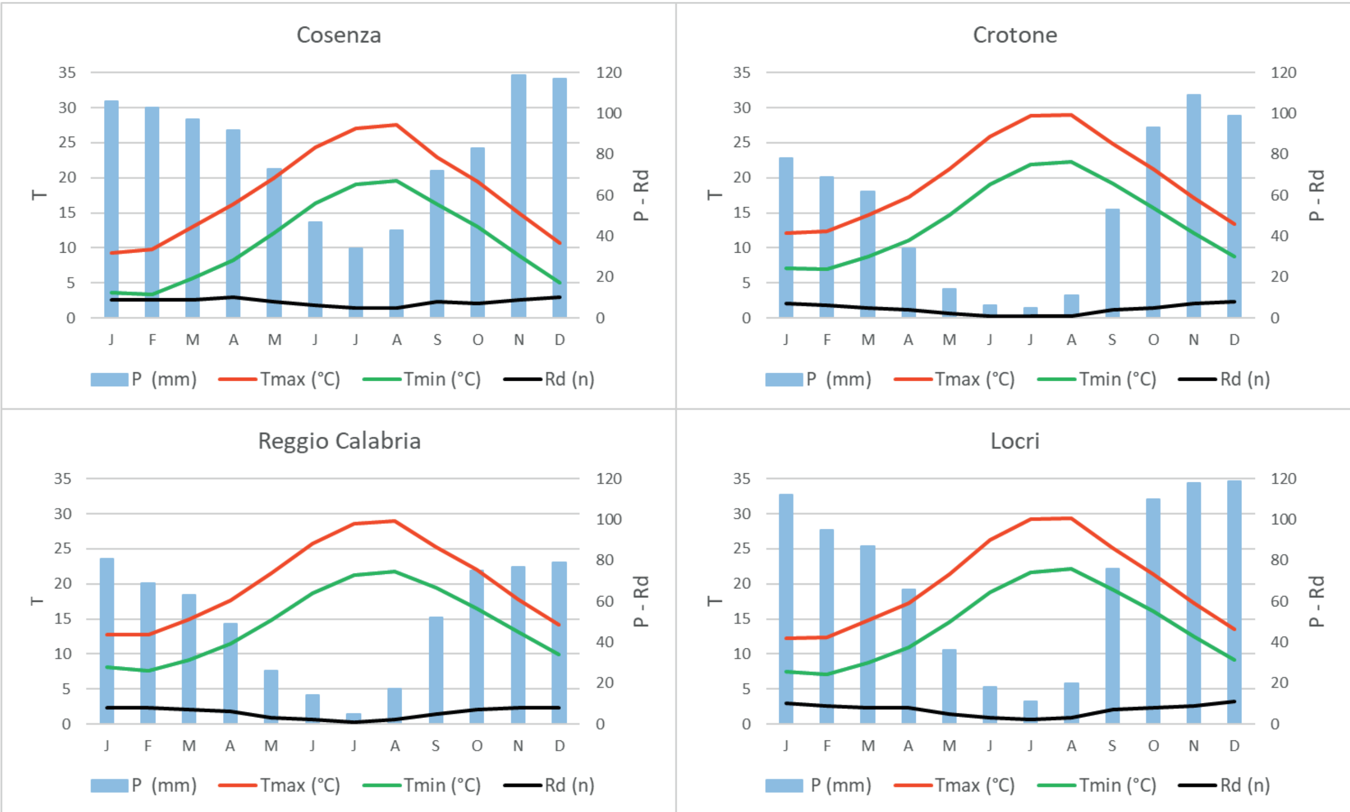

Fig. 2. Climatic diagrams of four meteorological stations covering the area where the majority of the fiumaras considered in this study are located. Rd stands for the number of rainy days

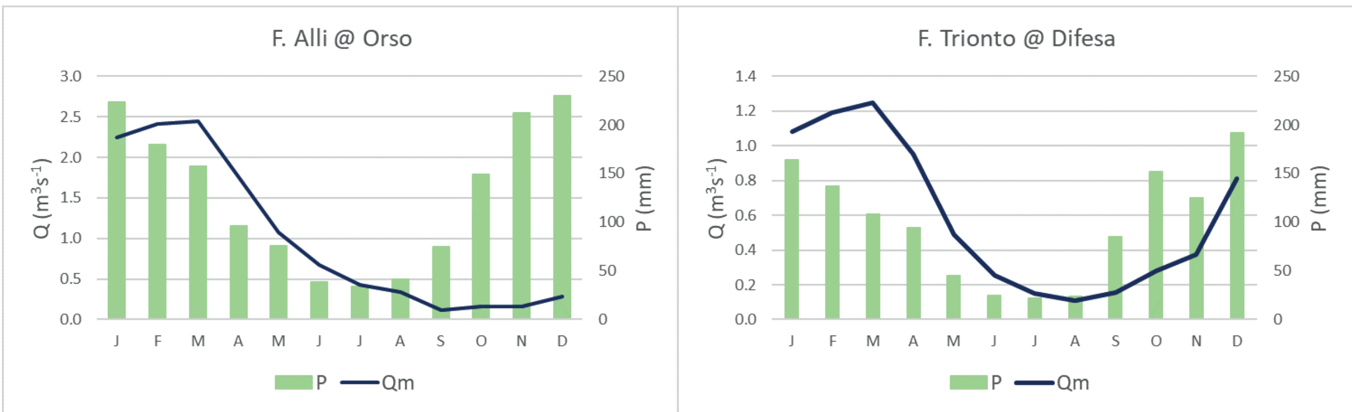

Fig. 3. Monthly variation of rainfall (P) and mean discharge (Qm) of the Alli and Trionto rivers. These rivers flow a few kilometers north and south of Catanzaro, respectively. The Alli River flow gauge at Orso undertakes a watershed area of 46 km^2, whereas the flow gauges of the Trionto River at Difesa undertakes a catchment area of only 31.7 km^2

Dataset 1 includes 18 rivers, and the measured parameters were (Table 1): catchment area (*A*); river length (*L*); average slope of the catchment (*S*); river gradient (*J*); maximum elevation in the catchment (H_{max}); maximum width of the river bed (W_{max}); average valley bottom width (W_v); drainage density (*Dd*) (ratio of the total length of the drainage system to the catchment area); length of the terminal reach (*Ltr*); streambed gradient of the terminal reach (*Jtr*); catchment shape factor (*Sf*) (the catchment area divided by the catchment length squared (Horton, 1932) and relief ratio (*Rr)* (the highest minus the lowest elevation divided by the catchment length) (Schumm, 1956). Dataset 2 includes 37 rivers, but only data on catchment area, river length, catchment average slope gradient, river gradient, and elevation of the highest peak are reported. Tables 1 and 2 also report the mean, maximum, and minimum values and the variation coefficient (*CV*). All this data, except for the gradient of the terminal reaches of Dataset 1, were obtained from measurements on 1:10,000 topographical maps, integrated with observations from 1:33,000 aerial photographs. The shape factor was calculated as the ratio of the maximum basin length squared to the basin area (Horton, 1932). All the data were measured manually without the aid of any modern digital tool.

Field studies were conducted on four rivers with coarse sediments (Scilotraco, Simeri, Bonamico, and La Verde) to examine the alluvium stratigraphy , the occurrence of bedforms , and the grain size of the the riverbed. These rivers drain the eastern side of the Calabrian Apennine and flow into the Ionian Sea. Scilotraco and Simeri flow a few kilometers northeast of Catanzaro, whereas Bonamico and La Verde are located a few kilometers south of Locri (Fig. 1). In the Simeri and Scilotraco bed material samples were collected at 16 and 18 sites, respectively, for a total of 34 samples of surface material and 34 samples of subsurface sediment. The sampling sites are rather uniformly distributed along the main stem from the mouth into the Ionian Sea to about 7 and 8 km upstream in the Simeri and Scilotraco, respectively. The bed material samples were taken from the surface of a longitudinal bar located approximately in the middle of the streambed. Bed material samples were obtained from the Scilotraco and Simeri beds. The surface material was sampled by the transect line method (Leopold, 1970), including a minimum of 120 particles in each sample, whereas the volumetric method (Church et al., 1987) was used for the subsurface material. The size of each subsurface sample was such that the largest particle weight accounts for 10% of the total sample weight (Church et al., 1987). The volumetric samples were mechanically sieved by a mechanical shaker with sieves arranged on a ½ phi scale.

Table 1. Dataset 1

River	A, km^2	L, km	S, %	J, m/m	H_{max}, m asl	W_{max}, km	W_v, km	Dd, km/km^2	Ltr, km	Jtr, m/m	Sf	Rr
Abatemarco	64	21.5	41	0.0921	1980	0.21	2.60	5.82	10.15	0.0233	0.24	0.12
Alli	129	47.1	27	0.0340	1600	0.41	2.10	7.76	16.70	0.0090	0.10	0.04
Amendolea	150	41.2	36	0.0442	1821	0.95	2.75	7.17	19.45	0.0194	0.22	0.07
Arso	31	15.8	86	0.0506	800	0.20	3.60	6.81	7.40	0.0117	0.24	0.07
Avena	31	12.5	22	0.0760	950	0.42	0.68	6.04	10.20	0.0288	0.13	0.06
Favazzina	20	16.02	33	0.0971	1556	0.10	1.95	5.64	3.50	0.0626	0.11	0.01
Ferro	121	20.5	18	0.0561	1150	0.62	1.25	4.53	18.00	0.0228	0.32	0.06
La Verde	117	34.9	41	0.0560	1953	0.95	3.50	8.10	13.45	0.0117	0.19	0.08
Nicà	174	41.25	28	0.0279	1150	0.85	3.40	5.32	14.74	0.0063	0.32	0.05
Oliva	43	27.3	65	0.0480	1310	0.28	2.80	5.31	10.20	0.0217	0.16	0.08
Saraceno	86	19.5	89	0.0877	1710	0.40	4.10	5.42	18.80	0.0301	0.24	0.09
Savuto	405	72.4	55	0.0232	1680	0.35	8.15	3.31	27.30	0.0081	0.22	0.04
Scilotraco	18	13.9	73	0.0590	820	0.17	1.60	6.23	9.60	0.0090	0.11	0.05
Simeri	131	45.2	31	0.0365	1650	0.16	2.30	6.64	17.90	0.0098	0.12	0.07
Stilaro	95	28.1	33	0.0506	1422	0.35	1.95	5.93	16.55	0.0148	0.19	0.07
Triolo	18	10.2	7	0.0980	1000	0.05	0.60	5.78	2.15	0.0626	0.28	0.13
Trionto	279	40.5	18		1600	1.40	3.80	5.84	23.80	0.0163	0.30	0.05
Uria	60	27.8	53		1250	0.35	2.35	6.98	13.60	0.0103	0.16	0.06
Mean	110	30	42		1411	0.46	2.75	6.04	14.08	0.0210	0.20	0.07
CV	0.91	0.54	0.6		0.26	0.79	0.61	0.19	0.46	0.7962	0.36	0.41
Max	405	72	89		1980	1.40	8.15	8.10	27.30	0.0626	0.32	0.13
Min	18	10	7		800	0.05	0.60	3.31	2.15	0.0063	0.10	0.01

Table 1. Dataset 2

River	A, km2	L, km	S, %	J, m/m	H_{max}, m asl
Acrifa	17.32	10.77	25	0.0604	651
Allaro	130.18	36.91	31	0.0385	1422
Amusa	39.40	20.17	37	0.0615	1240
Annunziata	22.52	20.69	35	0.0673	1393
Armo	15.05	11.16	37	0.0869	970
Bonamico	136.42	30.16	39	0.0648	1954
Bruzzano	52.62	17.85	31	0.0662	1181
Calopinace	53.46	23.89	33	0.0656	1566
Careri	92.08	22.60	28	0.0691	1561
Catona	68.48	27.13	34	0.0676	1834
Condoianni	66.53	19.81	30	0.0533	1055
Fiumetorbido	7.76	8.80	42	0.0869	765
Gallico	59.63	25.22	39	0.0706	1780
Gerace	38.98	18.03	32	0.0549	989
Lume	8.16	8.15	31	0.0881	718
Macellari	8.30	8.20	29	0.1009	827
Melito	80.01	29.96	37	0.0560	1679
Menga	7.36	7.98	18	0.0727	580
Molaro II	7.14	8.74	32	0.0965	843
Molaro II	7.29	6.39	34	0.1185	757
Novito	55.86	19.55	31	0.0496	970
Oliveto	13.64	12.38	26	0.0728	901
Palizzi	36.46	18.81	46	0.0673	1265
Portigliola	35.02	19.05	34	0.0544	1036
Precarito	55.71	24.11	32	0.0573	1381
S. Agata	52.33	28.76	37	0.0586	1685
S. Elia	29.95	16.00	36	0.0635	1016
S. Giovanni	5.96	7.34	28	0.1095	804
S. Pasquale	25.88	16.26	39	0.0801	1303
S. Vincenzo	8.04	9.81	35	0.0904	887
Scaccioti	7.31	7.78	38	0.0972	756
Sfalasà	24.03	13.18	27	0.0893	1177
Sideroni	10.77	9.27	31	0.0836	775
Spartivento	16.39	12.89	39	0.0702	905
Torbido	160.52	26.20	35	0.0471	1233
Valanidi	29.07	20.61	33	0.0577	1190
Vena		9.44	32	0.1071	1011
Mean		17.14	36	0.0675	1137
CV		0.46	0.4	0.32	0.32
Max		36.91	89	0.1185	1954
Min		6.39	7	0.0232	580

RESULTS

Geomorphology

The ephemeral streams of Calabria have peculiar hydrological and geomorphological characteristics. These rivers, in fact, are dry for most of the time, and water flow is resumed only in response to very intense rainfalls, whose extreme peaks may reach and occasionally exceed 500 mm in one day and 150 mm in one hour. In their terminal reaches, the fiumaras have a braided morphology (Fig. 4) and are very wide and choked with coarse-grained (boulder to cobbles) sediment. The study rivers have a small catchment area and are rather short. The catchment area and channel length of most of the study rivers vary between 10 and 100 km^2 (range 6 and 405 km^2, mean 63 km^2) and between 10 and 30 km (range 6.4-72 km, mean 21 km) respectively (Fig. 5).

The recent uplifting of the Calabria region resulted in many short rivers with a narrow and elongated catchment with rather steep slopes (Versace et al., 2017) (see Fig. 1) (see also the example of the Simeri River reported in Fig. 6 - Billi and Biamonte, 1995). The mean shape factor is 0.12 (range 0.06-0.23), which confirms the study that river catchments tend to a marked elongated and rectangular shape. The average relief ratio of the study fiumaras is high (0.07, range 0.01-0.13) (Table 1) and implies relatively high relief and steep slopes underlain by resistant rocks (Thomas et al., 2010). More than 57% of the study catchments have an average slope gradient in the 30-40% range (Fig. 7). It follows that the main channels also have high gradients (mean 0.0677, range 0.0232-0.1185) that are reflected by the steep gradient of the terminal reaches. The latter is obviously gentler, accounting for an average of one-third of the entire river gradient. Nevertheless, it is still quite steep, particularly for river reaches located just a few kilometers upstream of their outlet into the sea. The mean gradient of the terminal reaches is 0.021 and varies within the 0.0063-0.0626 range. For similar catchment areas, the terminal reaches of the Calabrian fiumaras are steeper than forested mountain rivers in the humid environment of northwestern USA mentioned by Hassan et al. (2005) (Fig. 8).

The steep gradient of the terminal reaches also accounts for their braided morphology (Fig. 4) and for the devastating energy of the flow during high floods. The high gradient of the terminal reaches results from the combination of recent uplifting and the high sediment supply propelled by the semiarid Mediterranean climate and the sparse vegetation on the catchment slopes. Dense forests cover only the highest parts of the mountain ranges. The terminal reaches are also rather short, 3.5-27.3 km, and high flood waves can quickly propagate through their lengths posing a serious threat to the coastal settlements.

The drainage density of Dataset 1 ranges between 3.3 and 8.1, mean value of 6.04 km/km^2. Drainage density is influenced by precipitation, rock permeability, slope gradient, and the scale of the topographic map used to measure it (1:10,000 in this study). Due to the interactions of these factors, drainage density is a highly variable parameter, and any comparison between data sets from different studies is also complicated by the use of maps at different scales. Nevertheless, according to the

Fig. 4. The Bonamico River is a typical example of a fiumara. It has a wide streambed and a distinctive braided channel morphology

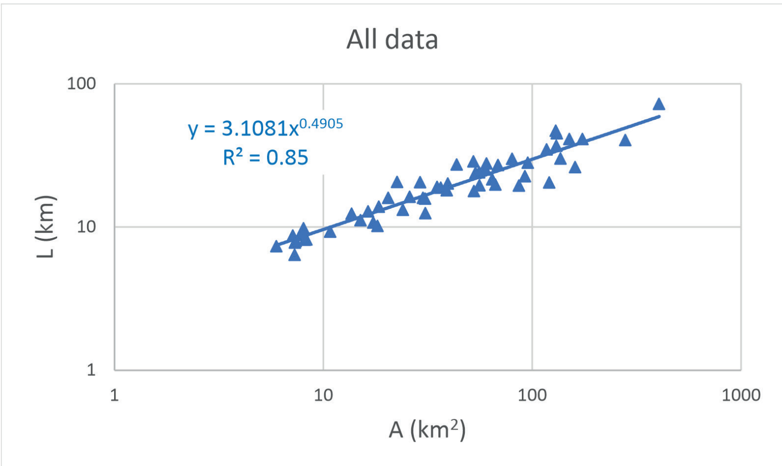

Fig. 5. Correlation between catchment area and river length

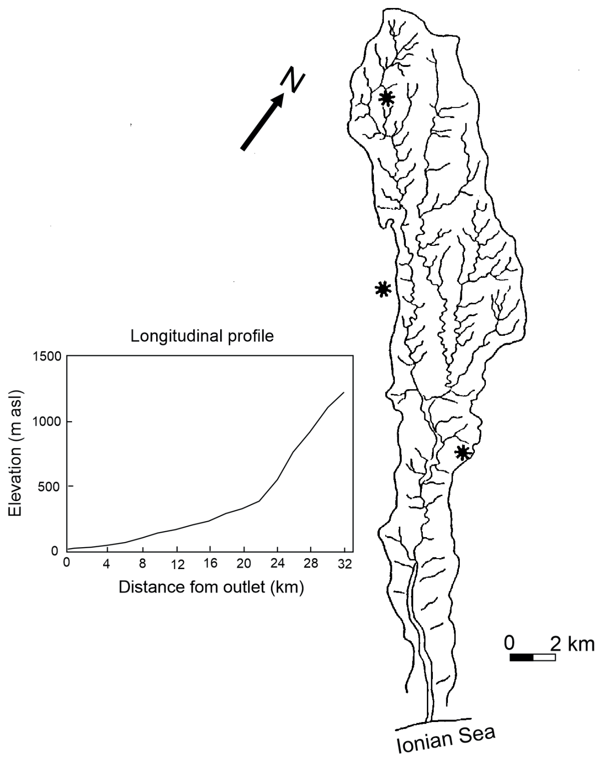

Fig. 6. Most of the Calabria rivers have a narrow and elongated catchment. An example is provided by the Simeri River. Rain gauges are indicated by the star symbols

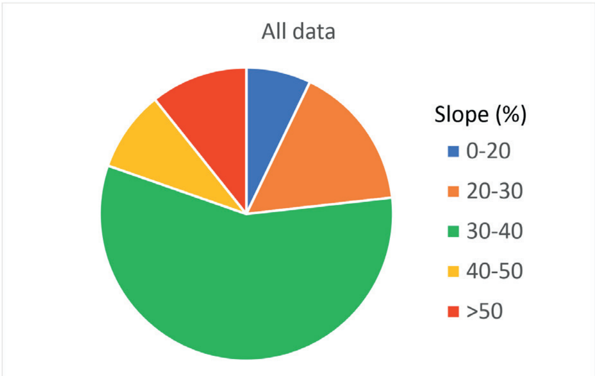

Fig. 7. Pie diagram of the average catchment slope variability. More than half of the catchment's average slope is in the 30-40% range

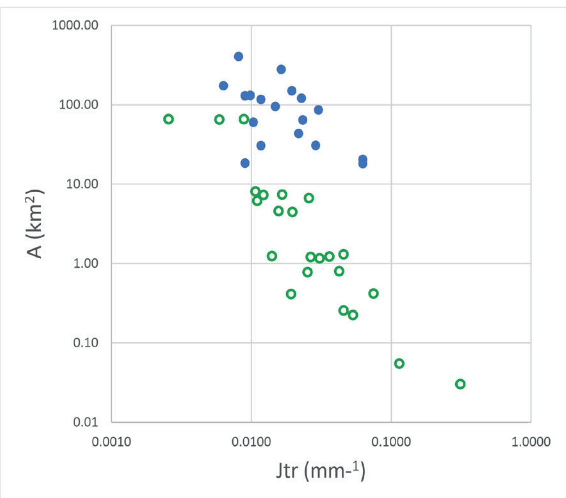

Fig. 8. Comparison of the fiumara data (solid dots) with the data of mountain rivers of the northwestern USA forested environment (open circles) (Hassan et al. 2005). For comparable catchment areas, the gradient of the fiumaras terminal reaches (Jtr) is substantially higher

classification of Ravi Shankar and Mohan (2006), a drainage density of 3.5 is considered a high value. For all but one of the Calabria rivers, drainage density is higher than 3.5 and for 16 out of 18 is higher than 5. This data indicates that the study rivers have a rather high drainage density, which, in general, implies a fast transfer of runoff from slopes to the main river stem, high river flow velocity, less infiltration, a short base flow period, and high unit peak discharges (Carlston, 1963). Such hazardous conditions result in higher floods, whose effects are exacerbated by the large proportion of the valley bottom taken up by the fiumaras. The ratio of the maximum streambed width to the average valley bottom width ranges between 0.01 and 0.50 (average 0.20). Infrastructures and urban areas are concentrated in the coastal belt, crossed by fiumaras spaced only a few kilometers apart, and, in the past decades, have been subjected to several destructive floods (Versace et al, 2017).

Sedimentology

Field investigations on the sedimentology of fiumaras were carried out in the terminal reaches of four rivers: Simeri, Scilotraco, La Verde, and Bonamico. The streambed of Scilotraco and Simeri was also sampled to obtain the grain-size distribution of surface and subsurface material (Fig. 9). In Fig. 9, we used the phi unit (phi = - $\log_2 D$, in which D is the particle diameter) since this is the classical unit used by sedimentologists and geomorphologists for investigating streambed armoring. The ratio between surface and subsurface median diameter (D_{50}) is also known as the armoring index and expresses the degree of surface texture coarsening. According to Parker and Kingeman (1982), a riverbed is considered armored when the surface-to-subsurface ratio is 2. The Scilotraco and the Simer show no or poorly developed bed armoring since their average armoring index is 1.7 and 0.9, respectively. Contrary to expectations, the proportion of sand does not influence the formation of an armored bed. In the Simer, the average proportion of surface and subsurface sand is almost equivalent (33.6 and 29.7%, respectively), whereas in the Scilotraco, the average proportion of sand in the subsurface is double that of the surface material (49.8 and 24.4%, respectively).

The stratigraphy of the study fiumaras was investigated by field observations of exposed cutbanks and dissected bars. The deposits of these ephemeral streams are characterized by tabular units consisting of horizontal, crudely bedded, imbricated coarse-grained gravel (Fig. 10) with occasional thin (10-50 cm), massive or horizontal laminated sand lenses (Fig. 11). The gravel layers are commonly reversely graded with the largest boulders resting, especially on

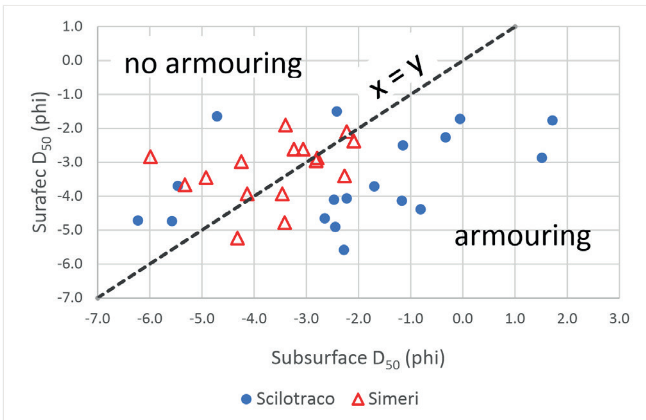

Fig. 9. Distribution of the surface to subsurface D_{50} ratio in the Simeri and Sciolotraco rivers

top of the highest bars (Fig. 10). The study rivers' gravels are poorly organized, poorly sorted, clast-supported, and, subordinately, open-work or infilled with fine grains and locally matrix-supported (Fig. 12). Imbrication is not ubiquitous. In places, the gravel particles within the tabular beds are chaotically arranged, and imbrication is absent (Fig. 11). The tabular beds are 20 to 80 cm thick, and their erosive base is indistinct. The structureless, chaotic gravels reflect deposition under high flow energy and high sediment supply conditions, whereas the open-work gravels are deposited by quickly slowing flow and winnowing of fines (Maizels, 1993; Carling, 2017), leading to an armor layer.

The bar top is typically coarser than surface material of the channel bed (Fig. 13). In the Scilotraco, the average D_{50} is 11.3 and 1.1 mm, respectively, whereas in the Simeri it is 9.4 and 4.2 mm, respectively. The bar top is on average 17 and three times coarser than the channel bed in the Scilotraco and Simeri, respectively. The concentration of the coarser boulders on the bar top (Fig. 13) confirms

Fig. 10. Horizontal, tabular stratification. The beds are reversely graded, and the erosive bottom of the top layer (yellow dotted line) is barely visible. The upper layer is polymodal, clast-supported, and poorly imbricated. The upper part of the sediment below the dotted yellow line includes an open framework and clast-supported gravel, which is part of a preserved armor layer

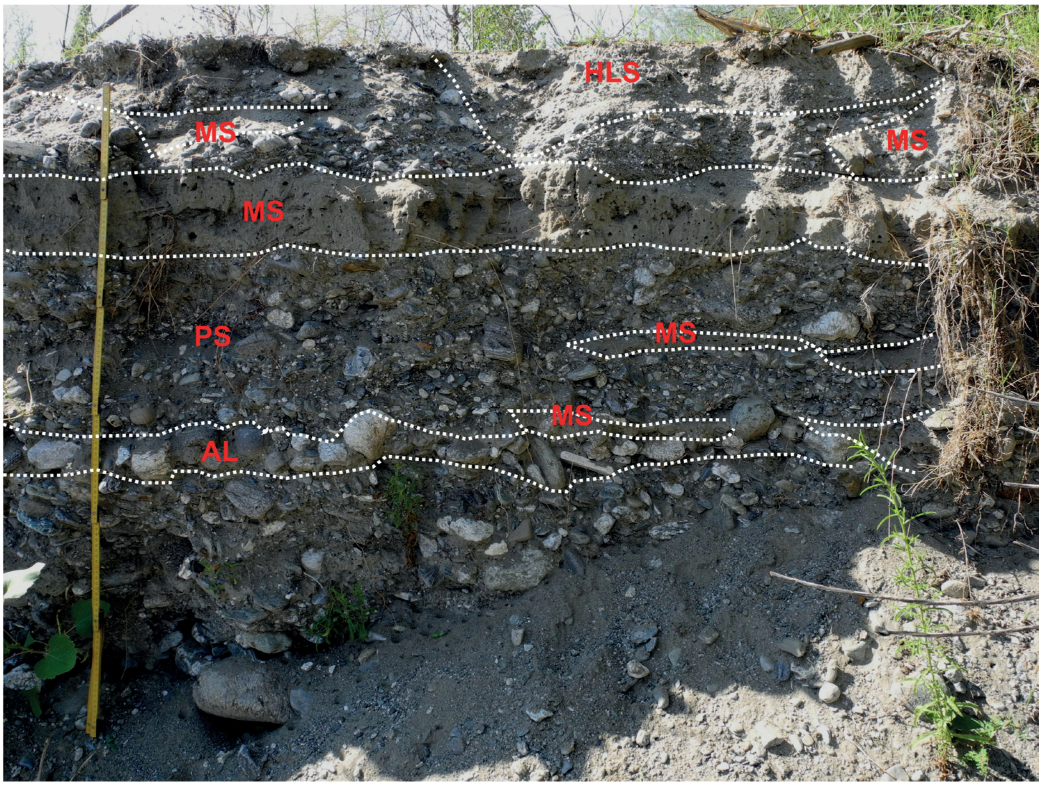

Fig. 11. Occasional occurrence of thin, spatially limited sand interbeds. MS = massive sand; HLS = horizontally laminated sand; AL = armored layer; PS = poorly sorted bed, no imbrication. In the PS, particle imbrication is not evident, indicating en masse bedload transport by hyperconcentrated flow

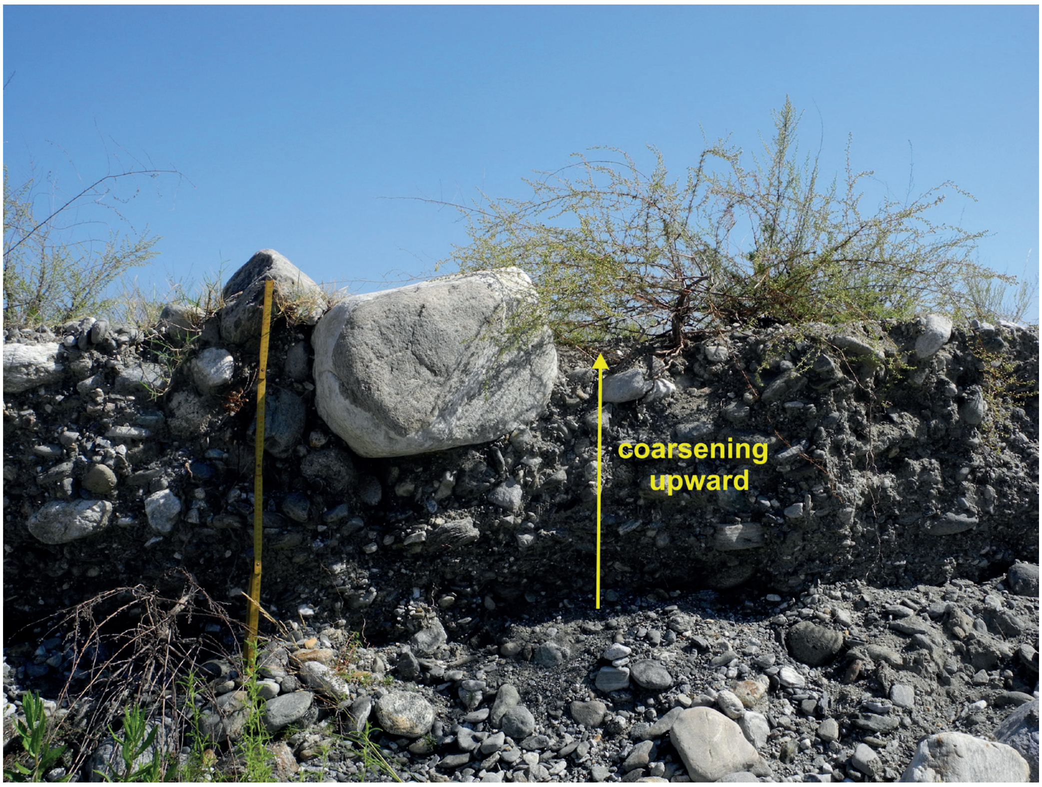

Fig. 12. Bar top layer. Coarsening upward is evident. The size of the boulder on top is close to D_{100}

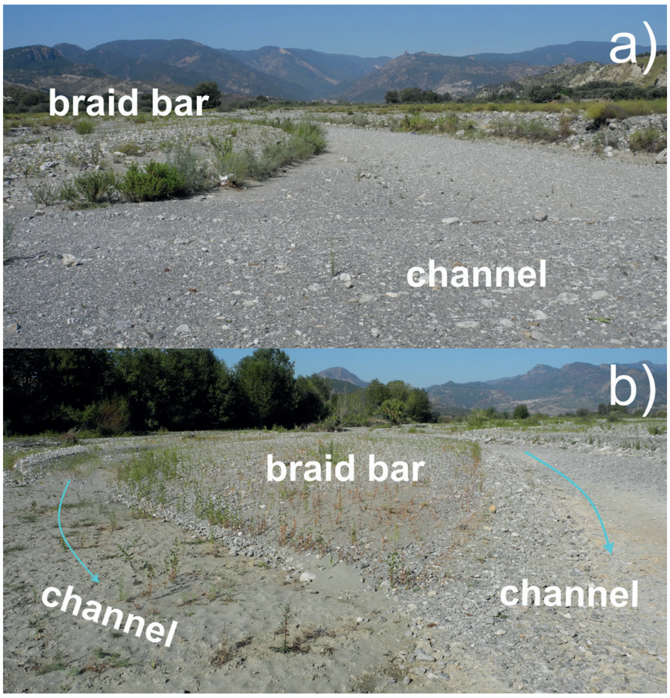

Fig. 13. Difference in surface grain size between channel and bar top: a) in the Bonamico River, the channel surface is filled with fine grains, whereas the bar top is covered with coarse boulders. Notice the vicinity of the basin headwaters to this channel section that is only a couple of kilometers from the sea; b) In the La Verde, bed material is finer. The secondary channels are locally covered with sand, whereas the main, larger channels are filled with fine grains and sand. Yet, notice the closeness of the headwaters

the large flow energy and shear stress experienced by the study rivers during floods. During low or receding flood flows, finer sediment is deposited in the channels, and, in some places, fine grains and/or sand drape the channel bottom (Fig. 13). The bars, by contrast, are not reworked. Their top surface material record the grain size of the bedload transported during high flows and winnowing of the finer particles as flow depth and velocity decrease. All these characteristics and the occurrence of the largest boulders (as much as 400 mm in mean diameter, equivalent to half of the active bedload layer) on top of the braid bars suggest en masse bedload transport and sedimentation from hyperconcentrated flows.

Riffle and pool sequences are not easily discernible for the common occurrence of channel filling with fine grains and coarse sand induced by backwater sedimentation at braided channel confluences (Fig. 13b, 14) and the crisscross overlapping of lobate gravel sheets, 20-40 cm thick. Very seldom, bars show a sand tail and downstream dipping foresets (Bluck, 1982), reflecting the lack of downstream accretionary fronts and the downstream migration of the longitudinal bars. Moreover, the gravel beds do not show any downstream fining in grain size. This evidence suggests that, in the Calabria ephemeral streams, bars result from the dissection of thick bedload sheets/layers (Whiting et al., 1988) rather than from the downstream migration of the longitudinal bars (Billi, 2016).

Sandy bedforms predominantly consist of plane bed, and only massive and horizontally laminated sand is present in the natural cutbanks (Fig. 11). In places, sandy foresets are found at the confluence of a minor braid channel into a major, deeper channel (Fig. 14). This sand is deposited by the backwater effect when the larger channel is still conveying a substantial discharge while the minor channel is flushing out during the receding flood flows. No ripples and dunes were observed in the study fiumaras, whereas streaming lineation and cuspate ripples were occasionally found only in the Scilotraco river mouth.

Gravel bedforms include pebble clusters (Brayshaw, 1984; Billi, 1987; Billi, 1988) (Fig. 15a), crescent scours (Picard and High, 1973) (Fig. 15b), transverse ribs (Fig. 15c) and keystone interlockings (Fig. 15d). Transverse ribs occur as individual lines of larger particles across the braid channel, unlike the sequences seen in gravel-bed rivers of more humid climate (Billi et al., 2014). In the study of fiumaras, the keystone interlocking is a very common coarse-grained bedform and consists of a larger key boulder with smaller contact particles around it. It is not clear how this combination of coarse and finer particles forms (Zimmerman et al., 2010) but, as pebble clusters and transverse ribs, they play an important role in increasing the streambed roughness and flow resistance.

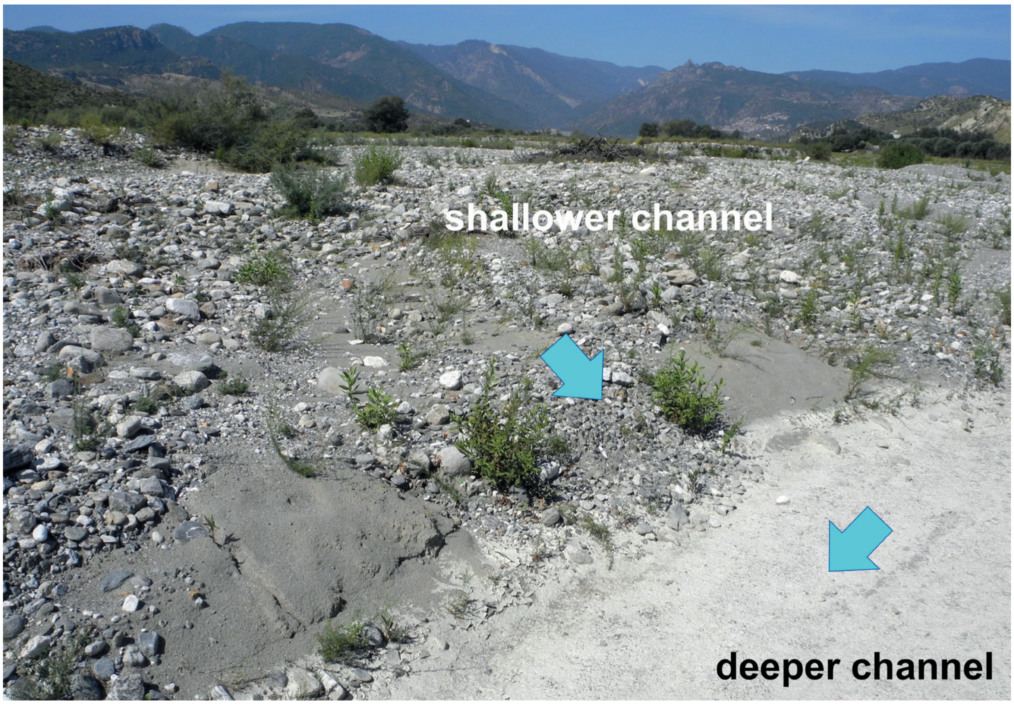

Fig. 14. Confluence of a shallow secondary channel into a deeper main braid channel downstream of a longitudinal bar. The backwater in the secondary channel favors the deposition of massive (or seldom, cross-laminated) sand

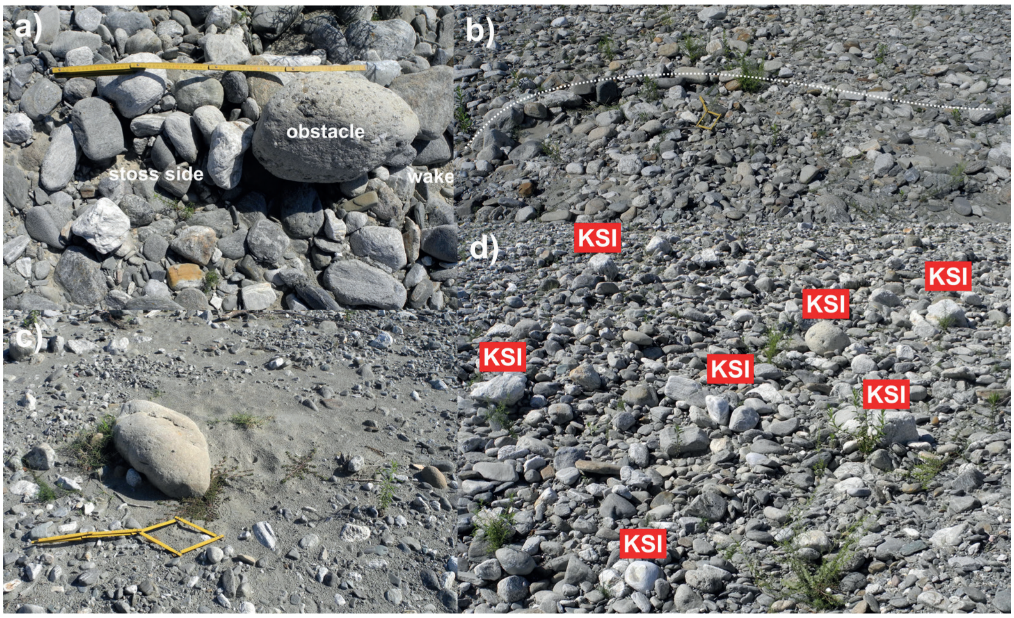

Fig. 15. Coarse-grained bedforms observed in the Bonamico and La Verde fiumaras: a) pebble cluster with the obstacle clast, the upstream stoss, and the downstream wake (Brayshaw, 1984). The stick ruler for the scale is 0.8 m. Flow from left to right; b) transverse rib highlighted by the dotted line across the channel. Flow is toward the reader; c) crescent scour. Notice the crescentic scour upstream of the boulder and the sand wake downstream. They are typically formed by shallow, receding flood flows. Flow to the right. The stake is about 0.8 m long; d) keystone interlocking. Several of these bedforms, consisting of a larger boulder surrounded by smaller particles are indicated by the notation KSI

DISCUSSION

In their study on the global distribution of rivers to terrestrial sinks, Nyberg et al. (2018) report the following relation between catchment area *(A)* and river length *(L)*: $L = 60.518A^{0.574}$

The study fiumaras also show a similar relation, though the coefficient (3.108) and the exponent (0.491) are somewhat different (Fig. 5). The difference in the coefficient can be explained by the larger data set of Nyberg et al. (2018) in which catchments with an area larger than 250 km^2 are by far the majority, whereas most of those considered in this study are less than 100 km^2 (only one is larger than 250 km^2 - Table 1). The exponent of the fiumaras is smaller, which indicates that, for comparable catchment areas, these rivers tend to be 30-40% shorter. The latter, in fact, exit the headwaters and cross the coastal plain with a short terminal reach, whose length is, on average, half of the total river length. Given the relief (high mountains close to the sea), the high drainage density, and the steepness of the terminal reaches, the transfer of water and large sediment loads (Sabato, 1989; Sabato and Tropeano, 2005) from the headwater to the coastal area during high flows is rather fast and capable of breaching the incoherent banks. Despite the small area of their headwaters, the geomorphic characteristics of the catchments and the lower channels lead the fiumaras to experience large, devastating floods.

The streambed gradient of the terminal reaches reported in Dataset 1 (Table 1) is typical of braided rivers (Rinaldi et al., 2016). However, some of them have steeper gradients, higher than 0.06, which in the literature are indicated as typical of single channels with step-pool or riffle pool morphology (Grant et al, 1990; Rosgen, 1996; Montgomery and Buffington, 1997). The ubiquitous occurrence of the braided morphology with river gradients typical of mountain streams can be accounted for by the lower, infrequent flow capability to entrain only a small portion of the incoming coarse-grained sediment load, resulting in high sedimentation rates. The downstream reaches of the fiumaras are, therefore, choked with sediment (Fig. 4) and reworked by lower-to-medium floods, mainly through channel incision (Fig. 14), providing them with the typical braided morphology.

The average drainage density of the study fiumaras is of the same order of magnitude as the rivers studied by Carlston (1963) in the northeastern United States. The latter, however, experiences a more humid climate with more uniform monthly precipitation compared to the Mediterranean climate of the Calabria region. Information about the drainage density of ephemeral and intermittent rivers is rather poor. Makhamreh et al. (2020) report rather low values of drainage density (1.49-1.85 km/km^2) for the Wadi Al-Shumar in northern Jordan. This river has a catchment with an elongated shape, similar to that of the fiumaras, but a lower maximum elevation of 1018 m asl. The annual precipitation of this Jordan River, 350-400 mm, is substantially lower than that of the Calabria rivers (especially in the headwaters). This can be considered as the main reason for the lower drainage density of Wadi Al-Shumar compared to the Calabrian fiumaras. Another factor leading to such a wide difference can be found in the smaller scale (1:25,000) of the topographic maps used by Makhamreh et al. (2020) whose detail about small streams is commonly inferior to a 1:10,000 map. Bedrock and soil characteristics are recognized by many scientists as key factors in determining drainage density, but, unfortunately, Makhamreh et al. (2020) do not report any information about them.

The streambed gradient of the terminal reaches of the study fiumaras is steeper than that of ephemeral streams of the same size investigated by Demissie et al. (2017) in the semiarid Raya graben in northeastern Ethiopia. The average gradient of the latter rivers is 0.013, whereas that of the study fiumara is almost twice (0.021). Both the study areas have been subjected to recent uplifting, but the Ethiopian ephemeral streams receive a lower average annual rainfall of 750 mm. The main reason for this marked difference in streambed gradient probably lies in the finer sandy gravel alluvium of the Raya graben rivers (average proportion of sand 59%) compared to the coarse gravel with very little sand of the Calabria fiumaras. The higher proportion of sand in the Raya ephemeral streams results from the hotter climate, the weathering-prone bedrock consisting of Eocene to recent volcanics, and the predominance of sparse bushy vegetation on slopes. For two large, predominantly sand and sandy gravel ephemeral streams draining the Daban basin in northern Somalia (Biyoguure and Kalajab), Billi (2022) measured a streambed gradient of 0.015. These rivers are very close to each other and share a similar bedrock mainly composed of Proterozoic granites and Eocene-Oligocene and Neogene sandstones and conglomerates. Very high temperatures year-round, modest rainfall only in the headwaters, occasional floods, and slopes without vegetation result in high sediment supply and aggradation rates. The predominance of fine sediment reflects the relatively lower streambed gradient, notwithstanding the Eocene to recent uplifting of the rift escarpment hosting the headwaters of both rivers.

The study fiumaras shares several sedimentological characteristics with other ephemeral streams in the world but also shows some differences. The structureless sedimentology of the alluvium, consisting of crude coarse gravel beds, typically 40-80 cm thick, poorly sorted, and organized is also reported by Hassan (2005) for his study of ephemeral streams in the Negev desert (Israel). Other similarities include the occurrence of the largest boulders on top of bars as observed by Billi (2016) in the boulder bed, seasonal Golina river crossing the Raya graben, or in the gravelly sand Biyoguure and Kalajab ephemeral streams (Billi 2022) in northern Somalia. According to Maizels (1993), the larger boulders are pushed upward by internal dispersive stresses. Manville and White (2003) consider the occurrence of large boulders on top of the active bedload layer as typical of hyperconcentrated flows. In the basal layer, these authors postulate debris flow conditions driven by internal inertial forces and the tangential boundary shear stress imposed by the overlaying turbulent flow. The particles larger than the basal flow are therefore pushed into the upper turbulent flow and move as contact bedload. In the fiumaras, the large boulders are rooted in the coarse core division of the tabular bed (Fig. 12) and the arrangement proposed by Manville and White (1993) is not evident. The presence of large boulders on the bar top of reversely graded beds seems to be better explained by the bipartite model of Sohn (1997) modified by Billi (2008) consisting of a frictional region at the base, above which, in the collisional region, the particle shear stress reaches its maximum. In this upper region of high shear stress, the largest particles are concentrated, with the outsized one protruding to the top of the active moving bedload layer. The winnowing of the receding flood flow contributes to removing the fines, leaving in place the coarse boulders, thus freezing a condition of high flow energy.

The alluvium of the Bonamico, La Verde, Simeri e Scilotraco fiumaras is typically structureless except for crudely bedded coarse-grained and poorly sorted gravels 05-1.0 m thick. These poorly organized deposits are also present in the Golina River and other ephemeral streams in the Raya graben, but in these rivers, the beds show a typical internal organization consisting of divisions with different grain size characteristics associated with the vertical distribution of shear stress in hyperconcentrared flows (Billi, 2008). This feature is not so well developed in both the Calabria rivers and the Daban ephemeral streams (Billi, 2022). The currently available data is insufficient to explain why the Raya graben riverbed load sheets exhibit such an internal organization. The floods of these rivers probably have a higher intensity and a longer duration, as they are generated by monsoon-type rainfalls, which allow for hyperconcentrated flows capable of some internal organization that is not possible in the shorter floods on the Calabria and Daban basin rivers.

The lack of evidence of downstream migration of braid bars is also observed in the Raya and Daban rivers, and Hassan (2005) also found bar dissection processes that, in the fiumaras and in the Raya and Daban ephemeral streams, are considered to form longitudinal bars through the incision of diverging and rejoining channels. The occurrence of large boulders on the bar top and the coarser grain size of the bar top with respect to the finer channel filling observed in the fiumaras has been reported for the Raya graben (Billi, 2016) and the Daban ephemeral streams (Billi, 2022) as well. In these latter rivers, the grain size difference between bar top and channel fill is not as marked as in the fiumaras and the Raya rivers. In the Daban, the predominance of sandy sediment over gravel and boulders, the very large width-to-depth ratio (close to 300) and the shallowness of the braid channel, especially in the widest reaches, may reduce the difference in shear stress between the high flow on the bar top and the low flow of the receding flood phase in the channels.

Crescent scours are typical bedforms of ephemeral streams. They are very common on the streambeds of the Daban and the Raya graben rivers, whereas they are rare in the fiumaras. Such a difference may be accounted for by the small percentage of sand in the Calabria rivers since the occurrence of a thick sandy top layer is fundamental for the development of this bedform, which is one of the most typical and indicative of dryland ephemeral rivers.

Ripples and dune bedforms are uncommon in the study fiumaras as in the Ethiopia and Somalia counterparts. The short duration of floods and, likely, flows with Froude numbers close to one are conditions unfavorable for the formation of bedforms, except for the plane bed (Billi, 2008). In places, mud film deposited in the pools shows shrinkage cracks. This bedform witnesses the flashy character of floods and the quick change from humid to dry weather conditions. The ubiquitous occurrence of crescent scours and horizontal lamination and the lack of cross-stratified sands and ripple and dune bedforms can be considered diagnostic elements to identify old deposits as originated by ephemeral streams. Typical sedimentological features of the fiumaras, though not exclusive to them, include the lack of a clear stratification, the occurrence of an armored layer including the largest boulders, especially on the bar top, the bed reverse grading, the lack of internal organization and downstream fining, the occurrence of pebble clusters, and keystone interlockings. From this study, it is evident that the study fiumaras share some distinctive characteristics with dryland ephemeral streams, but the former show a poorer diversity of internal arrangements and bedforms.

Field observations indicate that the streambed of fiumaras is not armored. In the Simeri and Scilotraco, bed material sampling and grain size analysis returned low average values of armoring degree (0.9 and 1.7, respectively) that are comparable to that of 1.7 reported by Hassan (2005) for a hyper-arid ephemeral stream in the Negev desert of Israel. According to this author, armoring may not be apparent in dryland rivers. In the Scilotraco, the armoring is more pronounced (1.7) than in the Simeri (0.9), but in the former river, the sand content in the subsurface material is twice that on the surface, and, in the latter, it is almost equivalent (around 30%). These data suggest that, in the study fiumaras, the proportion of sand trapped in the subsurface material is not sufficient to produce the formation of an armored bed. In more humid environments, the development of a coarser streambed surface is associated with selective transport and winnowing processes (Parker and Klingeman, 1982) or sediment supply-limited conditions (Dietrich et al., 1989). These conditions are rarely found in the ephemeral streams of arid and semi-arid environments. In the fiumaras, sediment supply is high, the infrequent flash floods are short, and flow vanes quickly constrain the occurrence of winnowing processes. All these conditions and the bedload en masse transport are supposed to contrast the development of streambed armoring.

The lack of an armored layer also has been found in other ephemeral and intermittent rivers and seems to be a recurrent characteristic of arid and semiarid region rivers (Billi, 2008, 2016, 2022). In these environments, sediment supply-limited conditions are rarely met because the sparse vegetation, long intervals without rain, and high rates of rock weathering result in high rates of sediment supply, especially if compared with the very low frequency of floods. Moreover, in arid and semiarid regions, lower than bankfull flows do not necessarily result in washing out the fines. A few field studies on dryland rivers (e.g., Billi, 2011; Demissie et al., 2017) indicate that, during shallow flows, the deposition processes tend to prevail on winnowing.

Another issue about streambed armoring is the occurrence of several check dams in the study rivers. The Calabria region is affected by intense erosion processes and high sediment delivery rates, so one could expect that after a few years/decades, when the check dams are filled, their influence on the sediment supply quantity and quality should tend to be neglectable. In 1973, a landslide blocked the upstream third of the Bonamico River and formed a small lake. Though this event initially may have substantially affected the sediment supply, time sequences of satellite images show that around 2010, the river started to retrieve its original channel morphology, and in the reach downstream of the landslide, there is evidence of a progressive change from very coarse bed material to finer sediment and of the restoration of a sediment supply, likely comparable to that typical of the river reach before the landslide. Besides, it is worth mentioning that a substantial sediment supply to the lower reaches of the Bonamico was and comes from its largest tributary, which is located downstream of the 1973 landslide and was not affected by it.

Further field studies, especially hydraulic field measurements and data, are strongly recommended to strengthen our knowledge of the geomorphological processes and the sedimentological characteristics of peculiar rivers such as the fiumaras.

CONCLUSIONS

Southern Italy's ephemeral rivers are known by the local name of fiumaras. This name is associated with short and steep channels that are dry for most of the time but capable of turning quickly into high floods with devastating energy. In addition to heavy rains and notwithstanding the small size of their catchment, geomorphic factors such as the high relief ratio, the steep slopes, the high drainage density, and the short and steep channel contribute to a fast transfer of water and sediment from the headwaters to the coastal plain reaches, resulting in channels chocked with sediment and high flood waves.

The alluvium of the fiumaras is coarse-grained, and its stratigraphy is very simple, as it consists mainly of horizontal, poorly sorted, commonly reversely graded, structureless beds with rare thin and spatially limited intercalations/lenses of massive or horizontally laminated sand. Crossbedding is very uncommon. The most common gravel bedforms are pebble clusters, keystone interlocking, and, subordinately, transverse ribs. Crescent scours, which are typical of dryland ephemeral streams, are seldom observed in the study fiumaras, probably because of the small proportion of sand. The largest boulders are typically found on the longitudinal bar top, whereas the main braid channels are filled with fine gravel and, subordinately, with sand.

The longitudinal bars do not show any evidence of downstream migration. They appear to result from the streambed dissection of thick bedload layers during the receding flood flow phase. The fiumaras' alluvium sedimentological characteristics indicate high rates of deposition from hyperconentrated flows. The fiumaras share some sedimentological features with coarse-grained ephemeral streams of other arid and semi-arid areas in the world, but further field studies are necessary to point out specific diagnostic elements for the interpretation of ancient deposits laid down by these peculiar Mediterranean rivers.

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