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Bedload transport and dune bedforms characteristics in sand-bed rivers supplying a retreating beach of the northern Adriatic Sea (Italy)

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ABSTRACT

Study Region: The coast of the Emilia-Romagna Region in northern Italy consists of about 210 km of sandy beaches that have been attracting tourists for decades. Since the 1980s, erosion processes resulted in a remarkable beach retreat, notwithstanding the construction of several protections works.

Study Focus: In 2005–2006 and 2017–2020, 30 floods of two small rivers feeding the beaches of Ravenna, Fiumi Uniti and Savio, were monitored and bedload was measured with a Helly-Smith sampler. Riverbed bathymetric surveys were carried out after some selected floods to investigate the occurrence and geometry of alluvial bedforms.

The dune migration method was also used to calculate bedload. Results provided by this method are very encouraging.

New Hydrological insights for the Region: To the authors knowledge, this field investigation on the bedload transport of small coastal rivers is the first one of this kind in the Adriatic and provides the regional land managers with a useful tool to predict the bedload yield for future scientifically based interventions, and hopefully successful, beach protection works.

The bedload data indicate a higher variability of bedload for discharges lower than bankfull flow, whereas a stronger control of discharge is evident for larger floods. Though the bedload of the study rivers proved to be higher than in the largest river of the Region, it resulted rather low and witnesses sediment supply-limited conditions.

1. Introduction

The beaches of the Italian northern Adriatic Sea are a very important environmental and touristic resource. In the Emilia-Romagna Region, the income generated by the beach holiday industry has always been a crucial component of the regional economy. In the last four decades, however, this asset has been substantially threatened by severe beach erosion and retreat (Gambolati et al., 1998; Armaroli et al., 2006; Balouin et al., 2006). In spite of the large number of beach protection works deployed, most of the Romagna beaches are still threatened by erosion. The reasons of such environmental degradation are manifold and a matter of debate between

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scientists and land managers. The sand supply from rivers is a crucial factor in the sedimentary budget of a beach but poorly known (Vorosmarty et al., 2003). The Romagna beaches are mainly fed by small sand-bed rivers but information about the sand flux of the latter is rather limited.

In the international literature, there are interesting studies on sediment transport in large sand-bed rivers (e.g. Lukanda et al., 1992; Molinas and Wu, 2010; Claude et al., 2012) but very few papers investigated the bedload transport processes of small coastal rivers and their role in the beach stability. A few authors, e.g. Church (2006), consider the sediment transport of sand bed rivers as "suspension dominated, with possibly significant bedload moving in the bedforms". Previous studies on sand bed rivers with dune bedforms of the Emilia-Romagna coast (e.g. Preciso et al., 2012; Billi et al., 2017) and unpublished data indicate that the sandy fraction accounts for less than 10 % of the suspended load grain-size distribution and consists only of fine and very fine sand. In the coastal rivers of the study area, the largest proportion of sand is transported as bedload and its measurement may contribute to understand and to quantify the potential supply of sand by small coastal rivers to the Emilia-Romagna beaches.

Quantification of the bedload transport, for effective management of rivers with sand-dominated bed material, is paramount and strictly interconnected with bedforms migration. Over time, several approaches and methods have been developed to quantify bedload but, due to the complexity and variety of the processes involved, no one universal method proved to provide reliable results for rivers with different characteristics (Gomez, 2006). Despite one of the most effective methods consists in direct field sampling (with bedload samplers), the occurrence of large bedforms such as dunes implies additional technical difficulties (Gaeuman and Jacobson, 2007; Muhammad et al., 2019) and a reduction of sampling efficiency (Hubbel, 1987; Gomez, 1991; Holmes, 2010).

In the Romagna alluvial coastal plain, rivers typically have very low gradients and a sandy streambed with moving alluvial bedforms (such as dunes), which suggest considering different approaches to asses bedload. One of the most popular methods involves the extraction of time-series elevation profile of the riverbed through echo sounding techniques (Simons et al., 1965; Van Den Berg, 1987; Dinehart, 2002; Villard and Church, 2003; Wilbers and Ten Brinke, 2003; Holmes, 2010; Claude et al., 2012; Guala et al., 2014), and bedforms geometry and celerity can be used to calculate bedload transport in natural rivers (Simons et al., 1965; Kostashuk and Villard, 1996; Ashworth et al., 2000; Julien et al., 2002; Parsons et al., 2005; Holmes, 2010; Wintenberger et al., 2015; Schippa et al., 2016). Notwithstanding these valuable studies, the development of models to estimate bedload transport by means of dune migration is still in progress and, to the knowledge of the authors, it has not been used in small coastal rivers (Holmes, 2010).

Field data on river dune characteristics are scarce and referred to few rivers (Gabel, 1993; Julien and Klaassen, 1995; Kostashuk and Villard, 1996; Amsler and Garcia, 1997; Carling et al., 2000), mainly because of the difficulties involved in the field measurements (McLean and Smith, 1979; Grinvald and Nikora, 1988; Kostashuk and Villard, 1996). As a consequence, dunes were more commonly investigated in laboratory flumes under controlled steady and uniform flow conditions (Gilja and Kuspilić, 2018; Guala et al., 2020). Moreover, a lack of comparative analyses between laboratory and field studies does exist, which is attributed to technical limitations (Sukhodolov et al., 2006; Holmes, 2010).

This paper presents the results of investigations on bedload transport and dune morphology through field measurements under different hydrometric conditions in the lower reaches of two small sand-bed rivers entering the Adriatic Sea in northern Italy (Cilli et al., 2018, 2020). Main aims of this study are: 1) to analyse the role of small rivers in supplying the sand to the beaches of the Emilia-Romagna Region; 2) to investigate the current river sediment flux deficit in terms of upstream supply vs flow capacity; 3) to test the reliability of the dune migration as an alternative method to assess the bedload transport of sand bed rivers. This information is crucial for a scientifically based management of an economically very important touristic coast of the Romagna region, which has been severely threatened by beach erosion in the last five decades (Gambolati et al., 1998; Armaroli et al., 2006; Balouin et al., 2006). The development of simple relations between flow discharge and bedload flux on the base of field data and the identification, among the currently most used bedload equations, of those capable of the best performance in terms of bedload prediction accuracy are useful and

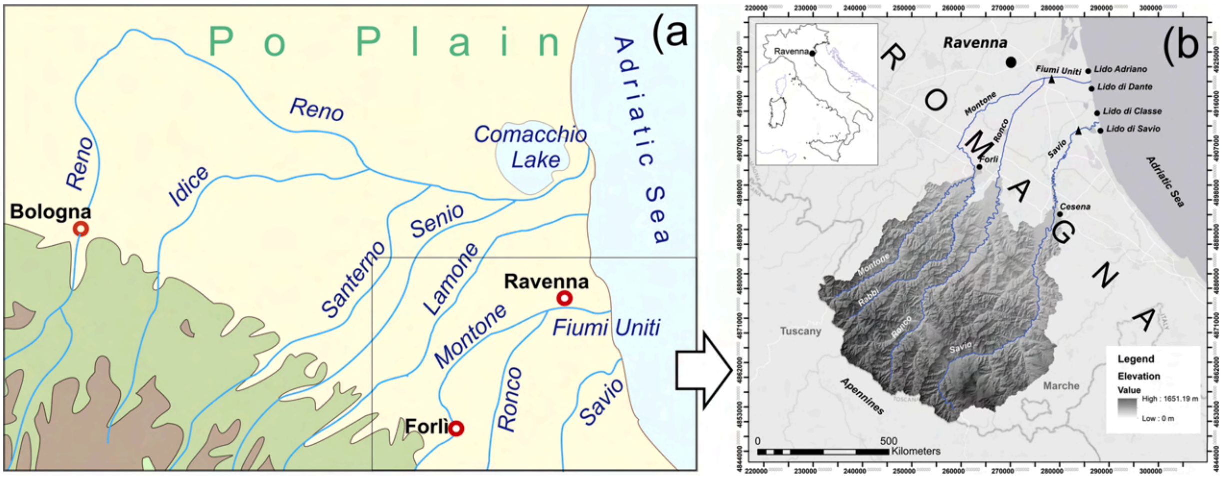

Fig. 1. Location maps: a) eastern Emilia-Romagna Region with the main rivers; b) the study rivers, Fiumi Uniti and Savio. The black triangles indicate the hydraulic and bedload measuring sites.

easy tools to carry out basic bedload investigations, which are preliminary to the design of new beach protection engineering works and to depict the sand supply variability throughout the past decades in relation to the implementation of past beach erosion countermeasures.

2. Study area

Fiumi Uniti and Savio are two small river systems located 50−60 km south of the Po River delta in the northern Adriatic Sea. They both originate from the northern Apennines and reach the Adriatic Sea after crossing the coastal plain of Ravenna (Fig. 1). The Fiumi Uniti River, with a catchment of about 1199 km^2, is the result of the man-made merging of the lower reaches of the Montone (532 km^2) and Ronco (625 km^2) rivers near Ravenna, i.e. 12 km upstream of the river mouth. In this latter reach, the river receives some water from the surrounding croplands of neglectable hydrological importance, so the total catchment area is slightly larger than the sum of Monton and Ronco catchments. The Fiumi Uniti River enters the Adriatic Sea between Lido Adriano and Lido di Dante (Fig. 1). The Savio River has a catchment of 625 km^2, is located a short distance to the south of the Fiumi Uniti and flows into the Adriatic Sea between Lido di Classe and Lido di Savio (Fig. 1).

In the headwaters, both rivers are underlain by Miocene turbidities (sandstones and marlstones); whereas the alluvial plain mainly consists of Pliocene marine deposits and Quaternary alluvial deposits (Amorosi et al., 2002). Mean annual precipitation is 1041 and 1005 mm for the Fiumi Uniti and Savio catchments, respectively. In both the study river catchments the monthly precipitation follows a typical Mediterranean pattern with a dry season from June to September, a monthly peak in autumn (in October) and a secondary peak in late winter (February) and a long spring rainy season from March to May (Fig. 2) (Mennella, 1972). Mean annual temperature is around 13.5 °C for both basins.

In the downstream reach of both rivers a few dams and hydraulic structures are present for irrigation purposes and to prevent salt-water intrusion. The most influential is the Rasponi sluice gate, located 3.5 km upstream the Fiumi Uniti river outlet (Figs. 3 and 4). All these dams are principally used for agricultural purposes and the local Land Reclamation Authority controls their opening and closing during the flooding season (i.e., from October to February) and the dry period (from March to September), respectively.

The sediment transport monitoring sites are located at pedestrian and road bridges placed 8 km (Fiumi Uniti) and 3.5 km (Savio) upstream of the river outlet, respectively (Fig. 4). At the measuring site both rivers have a straight channel with a rectangular cross-section (Fig. 4). The stream bed gradient is about 0.0003 for both the study rivers. Bed material is sand, with a median diameter (D_{50}) of 0.43 mm in the Fiumi Uniti and 0.26 mm in the Savio.

The tidal excursion of the Adriatic Sea along the coast of the study area is very limited as it does not exceed 0.7 m. Although the tidal range is almost negligible, backwater effects are present during low flow conditions but are irrelevant during floods.

3. Methods

3.1. Field measurements

The streambed gradient was measured with a total station and bed material samples were collected by a US BMH-60 sediment sampler. Bed material samples were collected at each measuring vertical considered for the sediment transport monitoring and merged together to obtain a representative sample of the river cross-section. The samples were dry sieved with a Ro-Tap shaker using sieves arranged on a ½ phi scale. In the Fiumi Uniti, field measurements of bedload transport, flow hydrodynamics and streambed morphological changes were carried out in 2005−06 (Billi et al., 2017). A new measuring campaign on both the Fiumi Uniti and the Savio rivers started in 2017 and lasted until the early 2020. During floods, hydraulic and sediment transport data were collected along

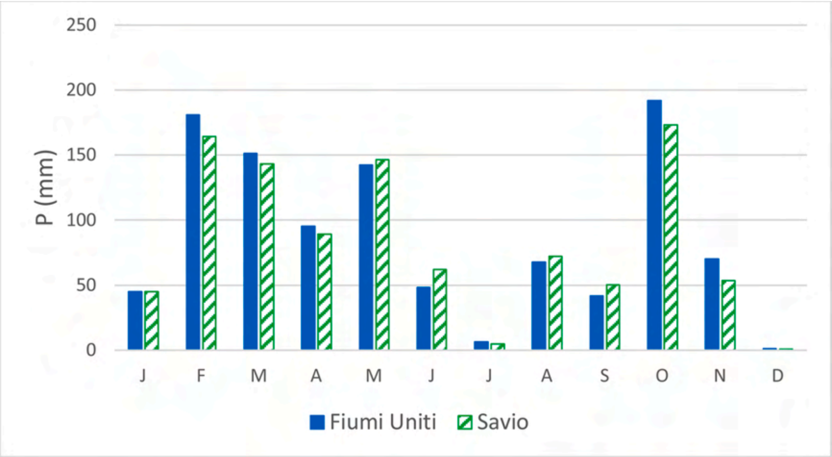

Fig. 2. Monthly precipitation distribution in the study catchments.

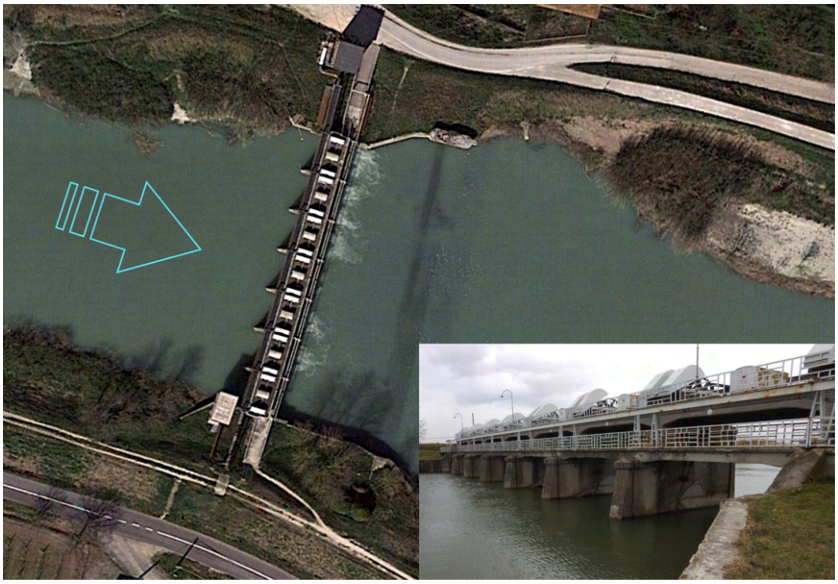

Fig. 3. The sluice gate on the Fiumi Uniti. The blue arrow indicates the flow direction. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

established verticals, equally spaced across the active portion of the streambed (Fig. 4). Flow velocity was measured at each vertical by means of a standard USGS AA type current meter following the standard two-point method, i.e. measuring flow velocity at 0.2 and 0.8 water depth (*H*).

Bedload transport was sampled at the same verticals immediately after the measurement of flow velocity. A standard Helley-Smith bedload sampler (US BL-84) was used. It had a 76 × 76 mm intake, 0.1 mm of bag mesh and an expansion rate of 1.10, which is considered to have the highest efficiency (Emmet, 1979). The hydraulic measurements were taken from the bridges at variable time intervals according to the rate of water level change detected by a staff gauge installed on the bridges. Since the timing of bedload sampling largely depends on the flow conditions, it was calibrated after a few attempts: in case of high floods and substantial sediment transport rates the sampling duration was 10 min. Longer sampling times (as much as 20 min) were necessary for floods with low transport rates in order to ensure the collection of a sufficient sample volume (Boiten, 2003). Grain size distribution was obtained for each bedload sample by removing the organic matter and other alien materials and then by dry-sieving through a standard Ro-Tap shaker with sieves arranged on a ½ phi scale.

Bedforms and streambed morphological changes of the study rivers were surveyed at low discharge conditions in the aftermath of a few selected floods. Unfortunately, it was not possible to have these measurements during high flood flows due to safety reasons and to their very short duration. Bathymetric data were collected from a small inflatable dinghy equipped with an Ohmex SonarMite V1 single beam eco-sounder (sampling depth at 2 Hz). The bathymetric sounder was coupled with a DGPS (in RTK correction) for positioning. The instrument performed continuous recordings with ±0.05 m of accuracy (planimetric and vertical). Measurements were carried out both in zigzag and longitudinal tracks. The longitudinal tracks were parallel to the banks, whereas the zigzag tracks were carried out along a line making an angle of approximately 45° with the thalweg. The longitudinal transects were at 0.25, 0.50 and 0.75 width distance from one bank. The boat velocity was maintained constant, at about 2 m/s, in order to ensure the stability of the vessel and the accuracy of the measurements. The surveyed reaches were located right upstream of the measuring sites and were about 1 km long (Fig. 4). The rather short (a few hours) receding flood flow prevented the dune bedforms from reworking. Moreover, the asynchrony between the flow conditions and the dune geometry, which is commonly observed during flow level changes in large rivers (Kostaschuk and Ilersich, 1995) and flume experiments (Allen, 1982; Hu et al., 2016; Reesink et al., 2018), makes it possible to associate the dune geometry surveyed during the late receding flood phase with close-to-peak flow levels.

The bathymetric data were post-processed with a five-data point moving average filter and interpolated with ArcGIS software through a topo-to-raster interpolation with a 0.5 m grid. The interpolated streambed surfaces were used to evaluate the presence of bedforms which were assumed as immobile at low flow. The collected data enabled to calculate the average dune height and wavelength.

3.2. Hydrodynamic modelling

To compare the measured sediment transport, the observed dune morphology and kinematics with bedload and bedform predictors, it is necessary to derive the involved hydrodynamic parameters (e.g. Froude number, energy grade, bed shear stress, stream power). To this aim an integrated approach involving GIS and a quasi-steady flow routing model (i.e. HEC-RAS) was used to determine the hydrodynamic condition along the study rivers and to account for the backwater effects induced by the movable sluice gate dam on

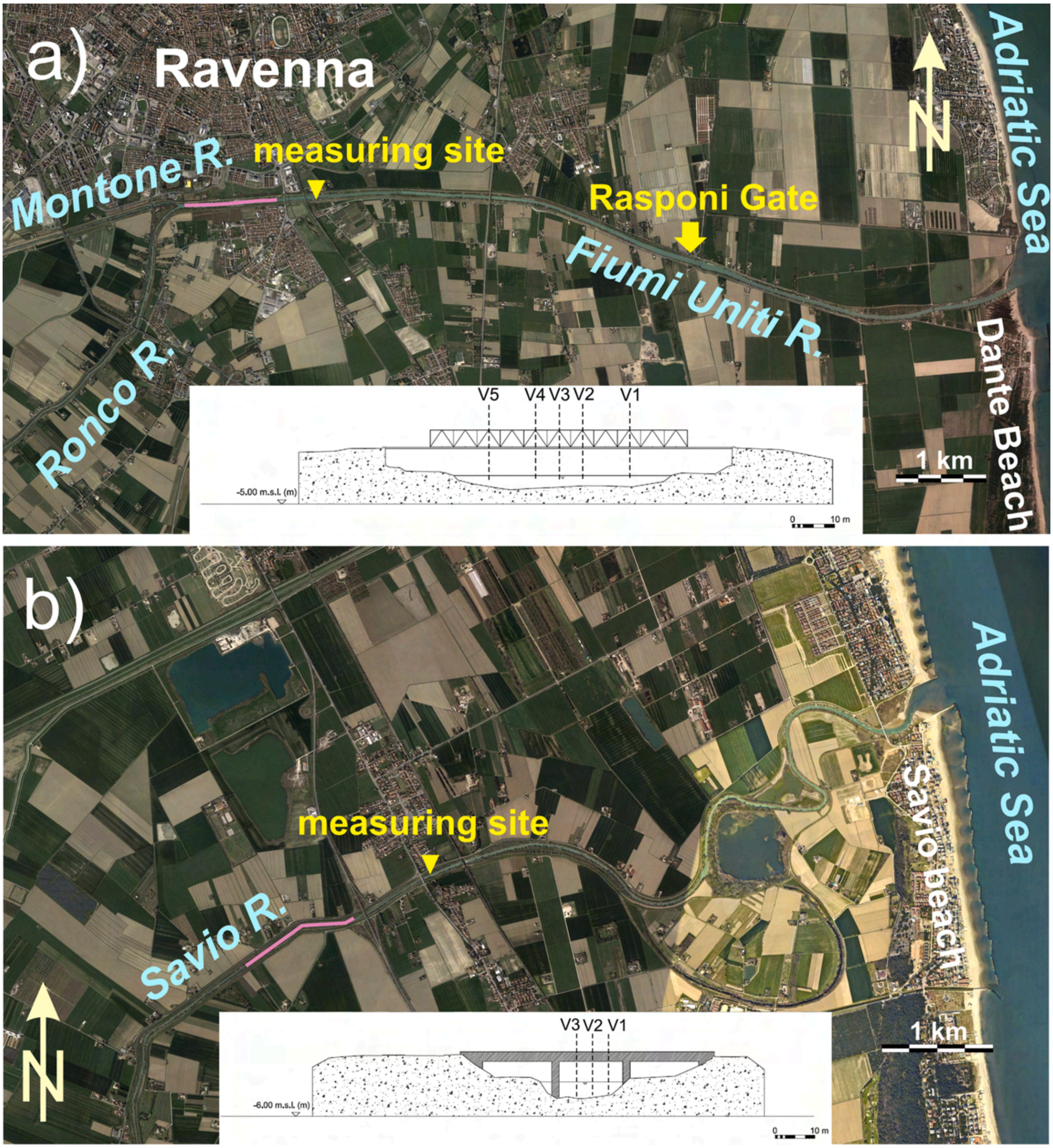

Fig. 4. Location and cross sections of the measuring sites: Fiumi Uniti (a), Savio (b). The bathymetric survey reaches are indicated by the pink line. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

the Fiumi Uniti (Fig. 3). The latter, according to its operating schedule, was maintained open for the entire duration of the flood season (autumn to spring) and closed in the summer to prevent the upstream intrusion of the saltwater.

The model was used to calculate the energy gradient and the bed shear stress in the river reaches across the measuring sites. A number of cross Sections (31 and 20 of the Fiumi Uniti and Savio, respectively) spaced about 300 m and surveyed by the Emilia-Romagna Region Watershed Technical Service were interpolated using a DEM imported into ArcGIS to obtain more closely spaced cross sections. The public 10 m resolution DEM provided by INGV (Tarquini et al., 2007, 2012) was merged with the river's cross-sections provided by the Basin Authority to build a continuous model including the river bed topography for simulations within HEC-RAS.

Boundary conditions were retrieved from the recorded flood hydrograph and sea levels. The model was calibrated using the observed water levels for 23 and 11 representative floods recorded in the recent years in the Fiumi Uniti and Savio, respectively. The Rasponi's sluice gate on the Fiumi Uniti (Fig. 3) was modeled as a boundary condition accounting for the actual operation rule. Moreover, the actual geometry of several representative river cross sections was verified by orthophotos, satellite images and on-site inspections. These data were used to calculate the roughness distribution along the cross sections wetted perimeter including the contributions of the floodplain areas. The assessment of the equivalent roughness was performed through the equivalent conveyance method. The model calibration was done adjusting the roughness coefficients to get the better match with the observed water levels. The calibration gave satisfactory results which allowed the determination of an equivalent Manning's coefficient equal to n = 0.019 $m^{-1/3}s$ and n = 0.029 $m^{-1/3}s$ for the Fiumi Uniti and Savio, respectively.

3.3. *Bedload transport as a function of dune bedforms migration*

The sediment transport involved in dune migration over medium-to coarse-grained sand bed river is generally assumed to represent bedload transport (Van Den Berg, 1987). Several studies have been proposed formulating theoretical models for flow over dunes (McLean and Smith, 1986; Nelson and Smith, 1989; Mendoza and Shen, 1990) but only a few researchers linked sediment transport with self-formed bedforms (Kostaschuk and Ilersich, 1995; Holmes, 2010; Aberle et al., 2012; Leary and Buscombe, 2020). Assuming dunes as two-dimensional bedforms with a longitudinal triangular shape and steadily propagating downstream, bedload transport can be quantified through dune characteristics using the sediment continuity formula proposed by Simons et al. (1965), i.e. the modified Exner's (1925) equation, which has been largely used in literature (e.g., Van den Berg, 1987; Dinehart, 2002; Villard and Church, 2003; Holmes, 2010; Aberle et al., 2012; Venditti et al., 2016):

$$q_b = (1\text{-}p)U_d\, h/2 \tag{1}$$

In which q_b is volumetric bed load transport rate per unit width; p is bed porosity (in case of sand bed is equal to 0.3 – Holmes, 2010); h is mean dune height and U_d is dune celerity. Dune geometry and celerity U_d can be obtained from field measurements or in laboratory flumes. In the scientific literature, there is no evident agreement on the calculation of dune celerity (U_d). In Table 1, dune celerity (U_d) equations considered for this study are reported. Among the several approaches available in literature, those based on Froude number (Fr) and on mean flow velocity (U) were used in the present study, since these parameters can be easily measured in the field. Moreover, the dune dataset of Gabel (1993) was reconsidered and a new fitting power law to calculate the dune celerity was derived (Table 1).

4. Results

4.1. *Flow and bedload field-measurements*

Measurements carried out in 2005–2006 and 2017–2020 resulted in a large (at least at the study area scale) dataset based on 23 floods monitored on the Fiumi Uniti (11 of which were measured by Billi et al., 2017) and 12 floods monitored on the Savio.

The flow discharge of the monitored floods ranged from 13 to 358 m^3s^{-1} in the Fiumi Uniti and from 7 to 234 m^3s^{-1} in the Savio. The largest flood of 358 m^3s^{-1} was one of the highest ever recorded in the Fiumi Uniti in the last decades (Billi et al., 2017). The 234 m^3s^{-1} flood can be also considered one of the highest of the Savio (Grottoli et al., 2020). In the Savio, an historical recording flow gauge is located a few kilometers upstream of the sampling site. It has a relatively long data record from which it was possible to calculate for the highest flood monitored a return interval of 12 years. In the Fiumi Uniti there is no recording flow gauge on its terminal reach. Recording stations are present, however, on the Ronco and Montone rivers but from these data it is difficult to extrapolate the return interval of the Fiumi Uniti floods, given the independent hydrological behaviour of the two main tributaries. On the base of the bankfull and maximum discharge regionalization presented by Billi and Fazzini (2017) for Italy, the flood flows of the Fiumi Uniti can be approximated to 1.6 time those of the Savio (this ratio also corresponds to that between the highest floods measured in the study rivers). From this data, we can presume a return interval of 20 years for the highest flood measured in the Fiumi Uniti.

Flow velocity varied widely between 0.2 and 1.66 ms^{-1} in the Fiumi Uniti and from 0.21 to 1.50 ms^{-1} in the Savio. Mean flow depth varied between 1.3 and 4.7 m in the Fiumi Uniti and from 1.99 to 3.96 m in the Savio.

Bedload transport was measured during 19 floods (out of 24) of the Fiumi Uniti and during 12 floods of the Savio. The data show some control of flow discharge on bedload transport rate. The relationship between unit bedload transport rate (q_b) and unit flow discharge (q) (Fig. 5) is expressed by the following interpolation equations:

Table 1
Equations to calculate the dune celerity (U_d) used in this study.

Source	Equation
Snishchenko and Kopaliani (1978)	$U_d = 0.019\, v\, \mathrm{Fr}^{2.9}$
Nikora et al. (1997)	$U_d = 0.66\, v\, \mathrm{Fr}^{2.9}\, (g\, L_w/v^2)^{-1}$
Carling et al. (2000)	$U_d = 5.67\, v^{2.04}$
Reinterpretation of Gabel (1993) data	$U_d = 0.0007\, v^{1.95}$

U_d = dune celerity; v = mean flow velocity; Fr = Froude number; L_w = dune wave length; g = gravity acceleration.

$$\text{Fiumi Uniti: } q_b = 0.0149\,q + 0.009\ (R^2 = 0.85) \tag{2}$$

$$\text{Savio: } q_b = 0.0024\,q\text{-}\ 0.0021\ (R^2 = 0.56) \tag{3}$$

In which q_b is the sediment transport rate in weight per unit with of the bed (kg $m^{-1}\ s^{-1}$) and q is the flow discharge per unit width ($m^3 s^{-1}\ m^{-1}$). Both correlations are significant at the 0.01 significance level.

The field measurements confirmed that bedload was active across the entire streambed only during the larger floods, whereas during smaller floods, only the central portion of the river bed was involved. Average bedload D_{50} is medium to coarse sand (0.51 mm in the Fiumi Uniti and 0.48 mm in the Savio) and it is coarser than bed material, which is 0.43 mm and 0.26 mm in the Fiumi Uniti and the Savio, respectively. No significant variation of bedload D_{50} and D_{90} with water discharge was observed (Fig. 6).

Previous studies (Preciso et al., 2012; Billi et al., 2017) in the Reno and the Fiumi Uniti rivers indicated that Martin (2003) equation and Mayer-Peter and Muller (1948) equation, modified according to Wong and Parker (2006), returned the best approximation to bedload field data. The upgraded data set of this study and the use of bed shear stress calculated through the hydrodynamic modelling described in Section 3.2 confirms the findings of these authors. Martin's equation provided the best predictions, especially for the Savio river (Fig. 7). This equation, though it overpredicts and underpredicts bedload for the Fiumi Uniti and the Savio, respectively, can be used to provide local technical administrations and professionals with a preliminary general information about the bedload flux to the beaches of the Romagna coast, since the geology, climate and channel processes of the study rivers are similar to those of the other small streams in the area.

In both the study rivers, the largest floods and the highest bedload rates tend to occur in spring, whereas bedload seems not to be much influenced by any seasonality (Fig. 8).

Though it is recognized by many authors (e.g. Robert, 2003) that bedload is largely controlled by the flow transport capacity, the study rivers and especially the Fiumi Uniti show a high variability of bedload transport rates which was also observed in other rivers and flume experiments (Fig. 9), though in the latter the range is rather small.

In the study rivers, it is evident that, at low discharges, flow is poorly correlated with bedload transport, whereas during higher

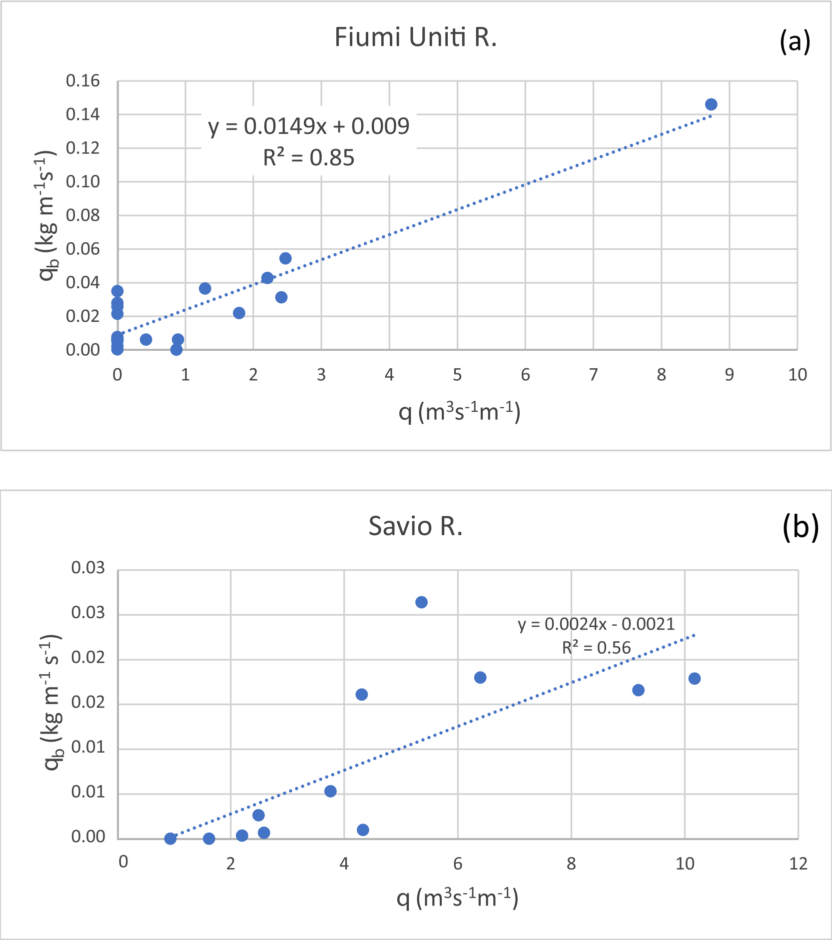

Fig. 5. Correlation between unit bedload transport rate (q_b) and unit flow discharge (q).

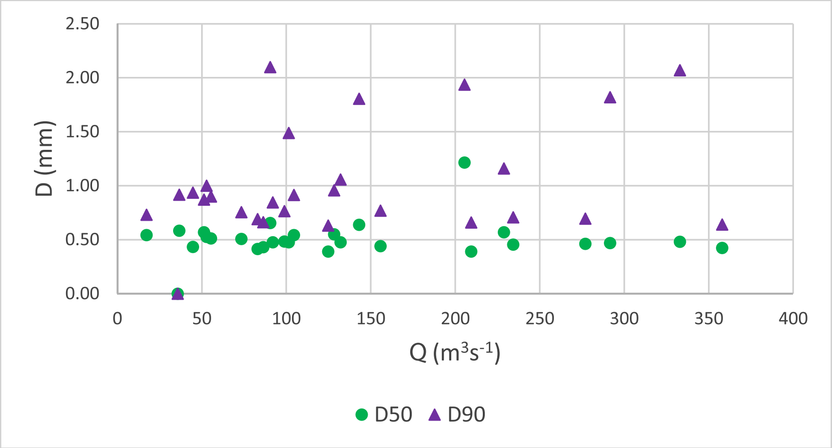

Fig. 6. Variation of bedload samples D_{50} and D_{90} with discharge in the study rivers.

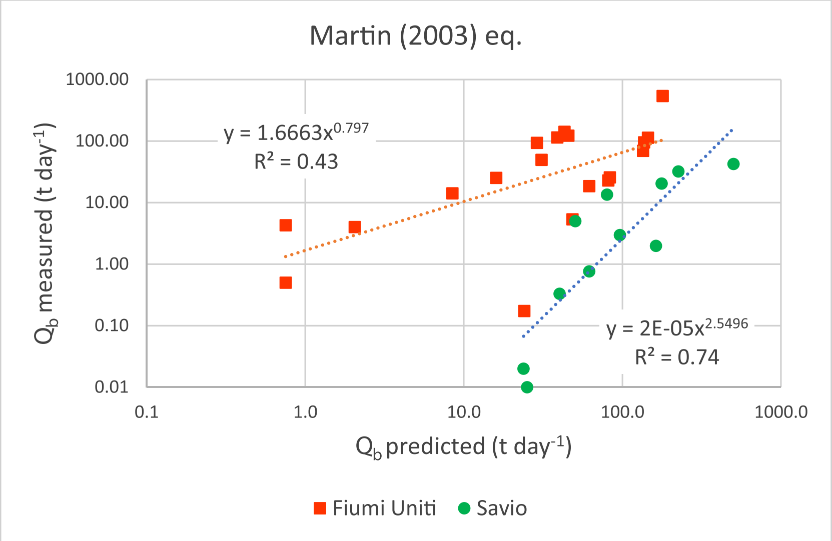

Fig. 7. Comparison between bedload field data and rates predicted by the Martin (2003) equation.

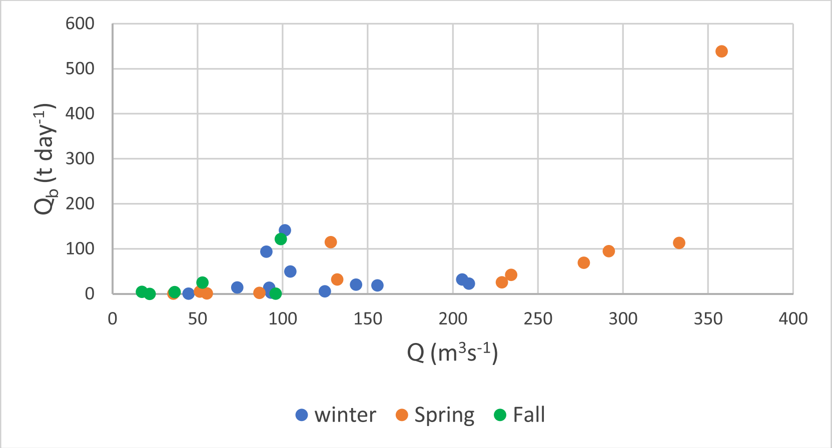

Fig. 8. Plot of bedload (Q_b) vs flow discharge (Q) data, grouped according to season.

floods, $Q > 200\ \text{m}^3\text{s}^{-1}$ (or specific discharge – Q_u – larger than $0.16–0.44\ \text{m}^3\text{s}^{-1}\ \text{km}^{-2}$) a consistent control of flow discharge on bedload transport is resumed (Fig. 10). In Fig. 10, few additional data from other small rivers located in the same region (i.e. Romagna) were included as well. These additional small rivers are: the Lamone (catchment area = 530 km^2) and the two most downstream tributaries of the Reno river, the Santerno (700 km^2) and the Senio (450 km^2) (Fig. 1). The catchment size of these rivers is of the same order of magnitude of the Fiumi Uniti and the Savio.

Another interesting result was obtained comparing the bedload data of the Romagna's largest river, the Reno (catchment area = 4628 km^2) (Preciso et al., 2012), with that of the small rivers considered in this study (Fig. 11).

The data in Fig. 11 show clearly that, for comparable discharges, the bedload contribution of the Reno river to the Romagna beaches is less than that of the small streams. The bedload measuring site on the Reno is located a few kilometers upstream of the Santerno and Senio tributaries confluence (Fig. 1 a), undertaking a catchment area of 3478 km^2, that is from three to six time larger than that of the small streams. The reasons for such a low bedload transport of the Reno were clearly exposed by Preciso et al. (2012) and primarily refer to the effects of an intense human impact in the catchment and on the main river channel. This evidence emphasizes the importance of the small streams in supplying the Romagna beaches with sand and point out the poor bedload transport of the Reno as one of the main components of the sediment unbalance along the study area coast.

4.2. Bathymetric survey and dune geometry

Four bathymetric surveys were carried out after selected floods: one in 2005 (Billi et al., 2017) and one in 2017 on the Fiumi Uniti and two in the 2017–2018 on the Savio (Fig. 12).

Table 2 reports the main data referred to the monitored floods, including also the highest one of 358 m$^{3s\text{-}1}$ recorded in 2005 by Billi et al. (2017) using the same field methods. The bathymetric data were interpolated in ArcGIS, obtaining a 0.5-m grid and smoothed profiles were extrapolated to obtain the dune geometry (Fig. 13). Bed profile data returned dune heights between 0.10 and 0.28 m for the Fiumi Uniti and between 0.12 and 0.16 m for the Savio. The mean dune wavelength was 15.41 m in the Fiumi Uniti and 6.65 m in the Savio, respectively. Dune steepness is about 0.007 in the Fiumi Uniti (except for the 2005 flood, which was about 0.02) and 0.02 in the Savio (Table 3).

The dune height and wavelength data measured in the study rivers were compared with a large dataset of river dunes available in the literature (Fig. 14) (Table 3).

The literature data refers to rivers in different environments: Jamuna and Parana (data from Julien, 1992); Bergsche Maas (data from Adriaanse, 1986 and reported by Julien, 1992), Meuse (Julien, 1992), Rhine (data from Wijbenga, 1991 reported by Julien, 1992), Calamus (Gabel, 1993), Fraser (Kostaschuk et al., 1989; Kostaschuk and Ilersich, 1995; Villard and Church, 2003), Liloet river in British Columbia (Prent and Hickin, 2001).

The study rivers bedforms geometry, though comprised within the wide range of the literature data (Table 3), shows extreme characteristics. Dune steepness, flow depth to dune height ratio and wavelength to flow depth ratio, in fact, are very close to the lower

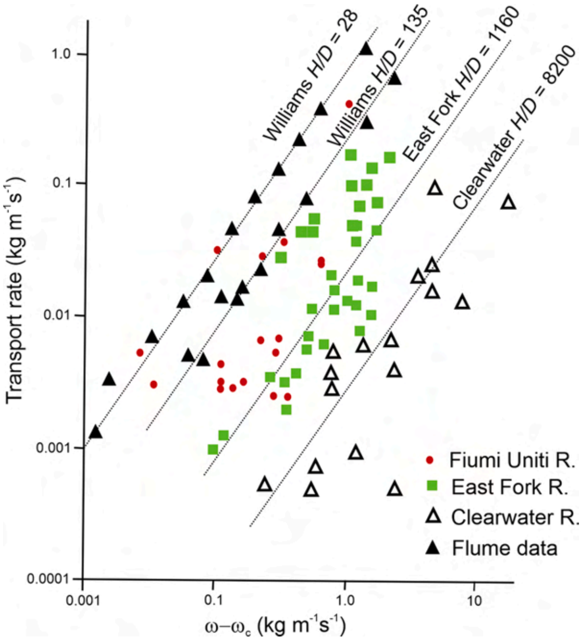

Fig. 9. Transport capacity expressed as excess stream power (ω−ω$_c$) vs transport rate. ω = unit stream power; ω$_c$ = critical unit stream power; H = flow depth; D = sediment size (usually D_{50}). In the Fiumi Uniti H/D = 6800. Modified from Robert (2003). Flume data from Williams (1970); East Fork and Clearwater data from Bagnold (1977).

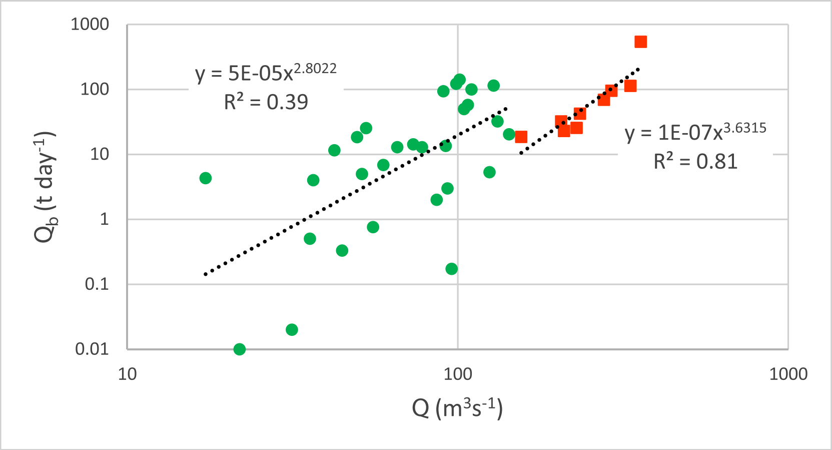

Fig. 10. In the small rivers of the Romagna region, at low flow (green dots), discharge has little control/influence/effect on the bedload transport rate. Vice versa, during high floods (red squares), bedload is substantially controlled by discharge. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

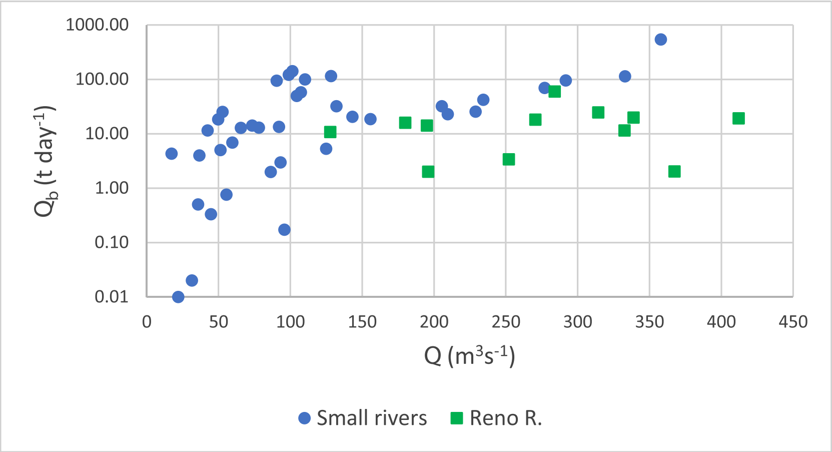

Fig. 11. Plot diagram of bedload transport rate (Q_b) vs flow discharge (Q) for the small rivers (Fiumi Uniti, Savio, Santerno, Senio and Lamone) and the largest river of the study area, the Reno R. (Fig. 1).

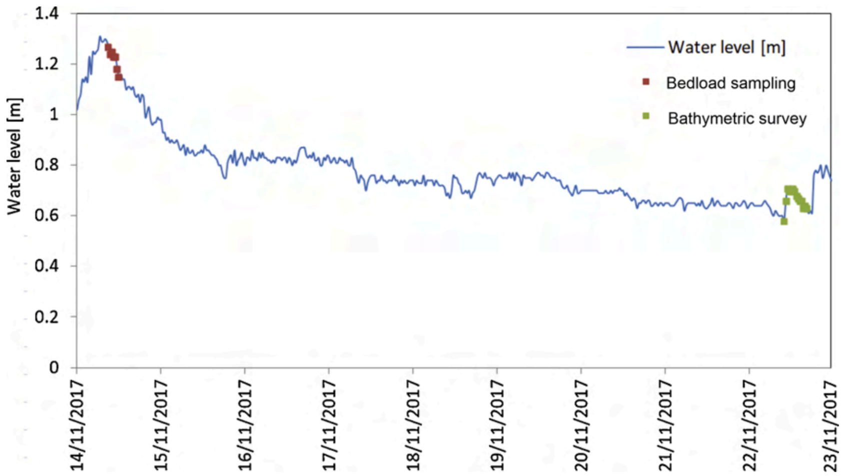

Fig. 12. Example of long-term flow hydrograph with bedload sampling and bathymetric surveys on the Savio River.

Table 2
Main flow and bedload data of the floods after which the streambed bathymetric survey was carried out.

River	Date	Q m^3s^{-1}	v $m\ s^{-1}$	H m	J $m\ m^{-1}$	Q_b $t\ day^{-1}$	D_{50b} mm
Fiumi Uniti	12/04/2005	358	1.66	4.72	0.00013	539	0.42
	14/11/2017	96	0.84	2.52	0.00005	1.43	0.57
	12/03/2018	291	1.34	4.09	0.00014	95	0.47
Savio	14/11/2017	22	0.61	2.30	0.00012	0.03	0.48
	12/03/2018	132	1.50	3.96	0.00035	32	0.51

Q = flow discharge; v = mean flow velocity; H = mean flow depth; J = energy gradient; Q_b = bedload; D_{50b} = bedload median grain size.

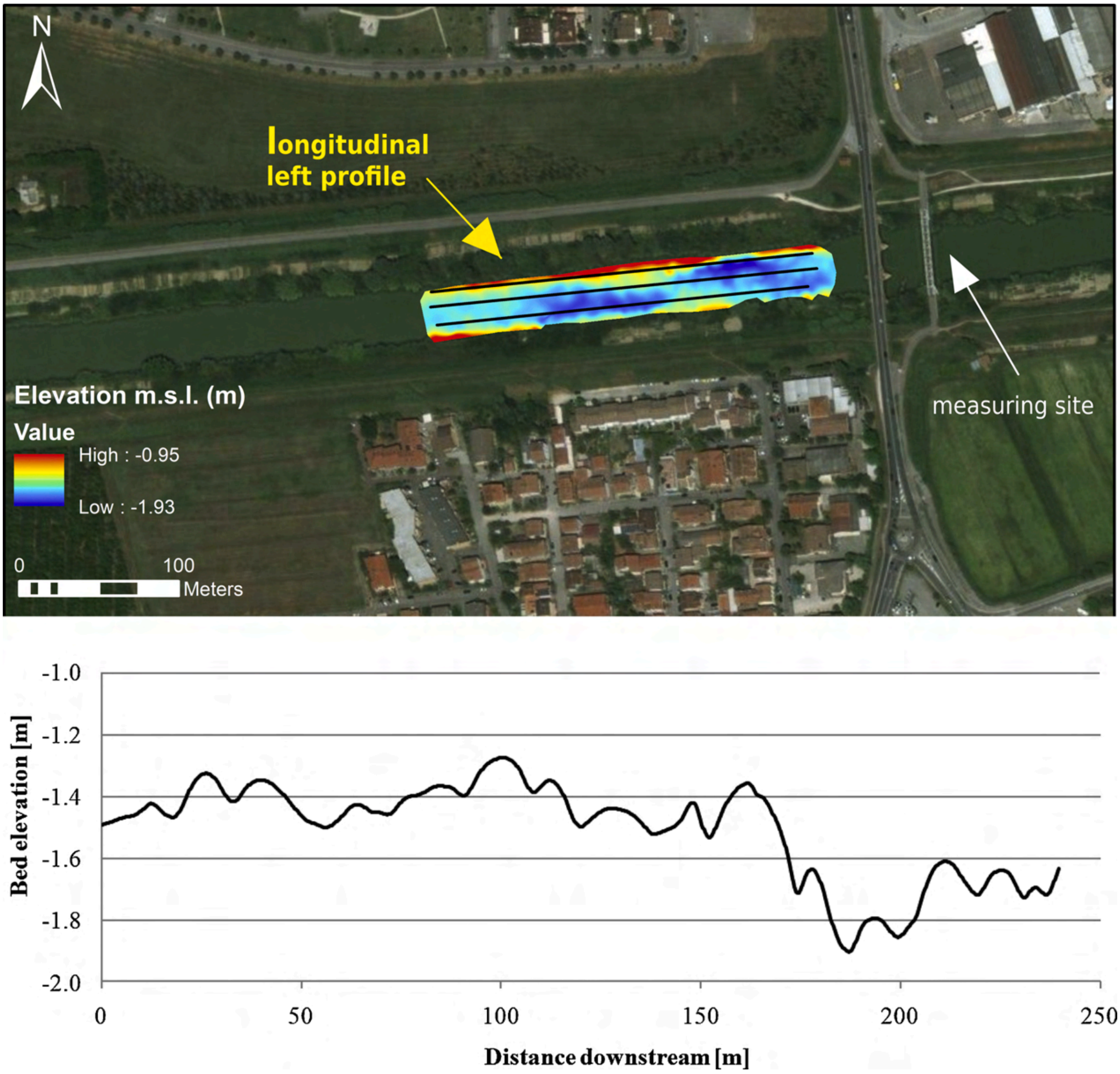

Fig. 13. Example of a longitudinal profile surveyed on the Fiumi Uniti after the flood of November 14, 2017, and the relative interpolated topographic surface (left profile).

values of the available literature data (Fig. 14). The study dunes have an average steepness of 0.015 and are comparatively flatter than the average dune of the literature data set (Fig. 14c). The flow depth to dune height (Fig. 14a) and the wavelength to flow depth ratios (Fig. 14b) are smaller than the mean values of the literature data. In the study rivers, in fact, flow depth is equivalent to 3.7 h_d (dune

Table 3
Dune bedforms geometry of the study rivers and field data from the literature.

		h_d (m)	L_w (m)	h_d/L_w	H (m)	H/h_d	L_w/H	Fr
Fiumi Uniti	12/04/2005	0.28	13.1	0.021	4.63	4.63	2.83	0.24
	14/11/2017	0.10	17.53	0.006	2.52	2.52	6.96	0.17
	12/03/2018	0.13	15.61	0.008	4.09	4.09	3.82	0.21
Savio	14/11/2017	0.12	6.14	0.020	2.08	2.08	2.95	0.14
	12/03/2018	0.16	7.16	0.022	3.58	3.58	2.00	0.25
Literature	mean	0.94	41.12	0.050	5.54	7.79	7.14	
	max	7.50	450.00	0.094	26.00	28.95	45.00	
	min	0.08	2.00	0.009	0.25	2.62	0.82	
	CV	1.12	0.30	0.280	0.76	0.52	0.89	

h_d = dune height; L_w = dune wavelength; h_d/L_w = dune steepness; H = flow depth; Fr = Froude number.

height) and wavelength is about 22.4 H (flow depth), that is about half and three times the average values of the literature. These data indicate that the dunes of the study rivers are thinner, shorter and flatter than those of other natural rivers and those produced in flume experiments (e.g. Kleinhans, 2001; Kleinhans et al., 2002).

4.3. *Dune bedforms migration and bedload*

The bedload transport data measured in the field (Q_{bm}) was compared with bedload transport predictions obtained by means of the dune migration method (Q_{bd}) (Eq. 1). Since no field data of dune celerity was available, dune celerity was calculated by different criteria reported in the literature: Snishchenko and Kopaliani (1978), Gabel (1993), Nikora et al. (1997) and Carling et al. (2000) (Table 1). The results obtained are shown in Table 4, in which the predictive performance (Q_{bm}/Q_{bd}) of the selected methods is also reported. From the data of Table 4 it is evident that Carling et al. (2000) equation, though underpredicting the actual values, provides the best results for both the study rivers with the best performance for the Savio (r values closer to one and shorter ranges).

The comparison between predicted and field bedload measurements, though based on few data, confirms that the dune migration method is a valid alternative approach to assess the bedload supplied by small rivers to the beaches of the Romagna region.

5. Discussion

5.1. *Bedload transport*

The majority of the beaches of the Emilia-Romagna Region are severely threatened by erosion processes that started several decades ago and became impressive in the 1980s (Gambolati et al., 1998; Armaroli et al., 2006; Balouin et al., 2006). The bedload transport measurements described in this study were aimed at understanding the role of this important component in the observed unbalance of the coastal sediment budget.

In both the study rivers, unit flow discharge and unit bedload transport are significantly ($p < 0.01$) correlated and Eqs. 2 and 3 can be used to obtain predictions of the sand flux to the local beaches. The good correlation between field data and bedload predictions by Martin (2003) equation, especially for the Savio ($R^2 = 0.74$; $p < 0.01$) is not unexpected, since the equation is based on unit stream power, which, in turn, is tightly correlated with unit discharge. However, in the Fiumi Uniti river, Martin's equation overpredicts bedload by a factor 1.65, whereas in the Savio it underpredicts bedload by a factor 16.7. At this stage of knowledge, there is no evident explanation for such a different performance of Martin's equation in the Savio River.

The field data also showed a high variability of bedload transport rate. In a Mediterranean environment, with a long dry summer and marked decrease in the forest canopy density in winter, some seasonality of bedload would be expected. In general, the spring rains resulted in the largest floods and highest bedload transport rates, even though high values were measured in any season, if prolonged or short but very intense rains occur. In Italy, and in the study area as well, Autumn is the season with the lowest vegetation protection in the cultivated land and the largest rainfall amounts and intensities. Nevertheless, low rates of bedload transport were recorded in the study rivers (Fig. 8). This result suggests a complex and still not fully understood relationship among sediment delivery from slopes, bed material entrainment, bedload transport and flow and partly accounts for the independent variability of flow and bedload transport.

Combining the study rivers data with few unpublished data of other small rivers in the region, different bedload/flow discharge patterns became evident for low and high flows. The latter show a significant correlation ($R^2 = 0.81$; $p < 0.01$), whereas for discharges less than 150 m^3s^{-1}, i.e. slightly larger than bankfull discharge ($Q_{1.58}$ ranges between 94 and 150 m^3s^{-1}), bedload is highly variable. Probably, during small floods, issues related to the bedload sampling on a sandy streambed with moving dune bedforms emerge. Though the Helley-Smith sampler used in this study is considered by Emmet (1979) as the type with the best performance, the inability to place the sampler in the correct sampling condition may result in bedload samples smaller or larger than the actual bedload, especially during little floods. Another factor to consider is the variability of sediment supply. Though the data show no seasonality effect, the occurrence of scours in the streambed may trap the incoming sediment, whereas their emptying may release larger than expected sediment quantities. Another aspect to be considered is the suspension of bed material given the turbulence induced by the

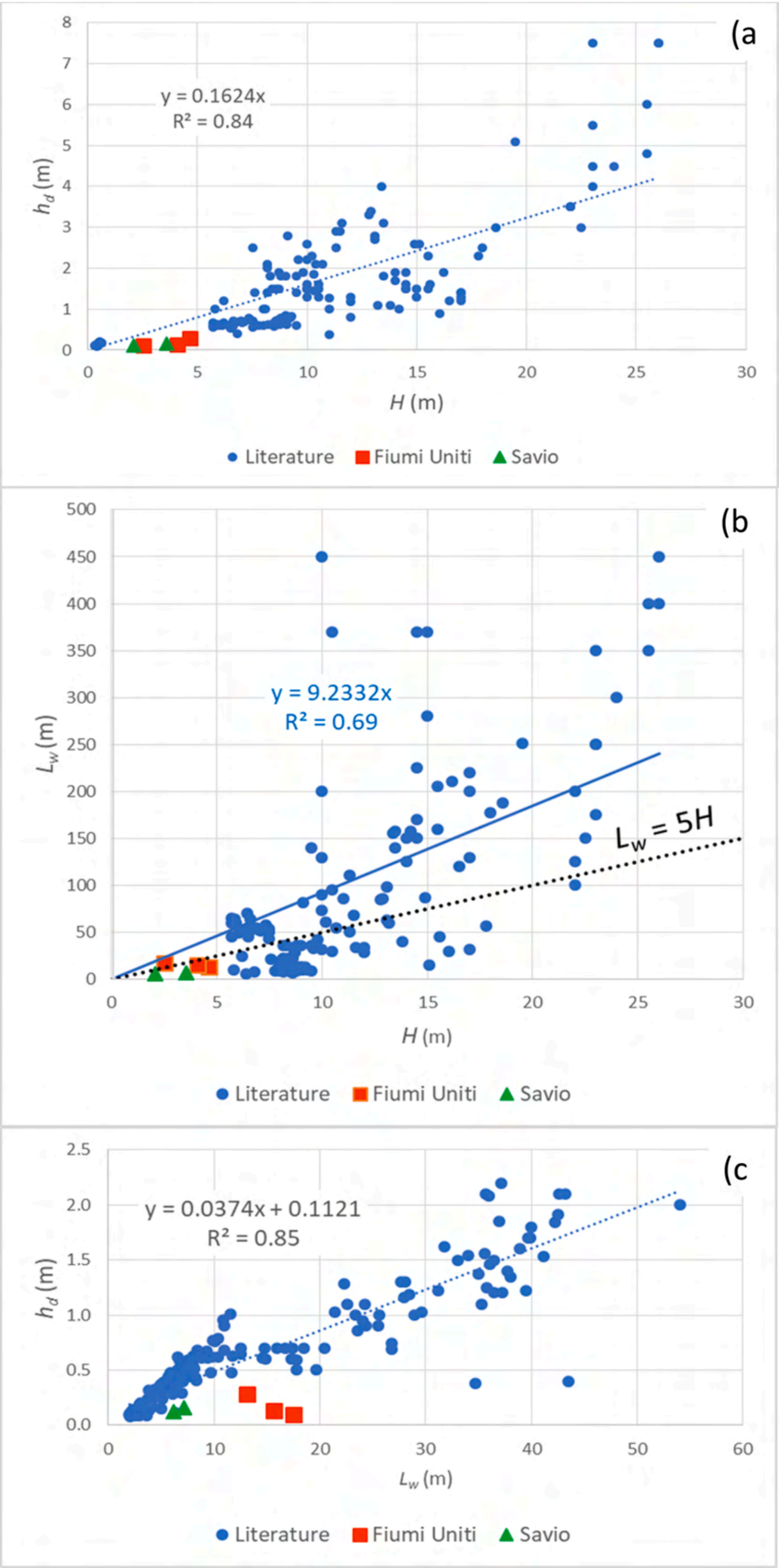

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Fig. 14. Correlation between dune geometry and flow depth: a) dune height (h_d) vs flow depth (H) from literature data of natural rivers and the study rivers. See text for the sources of literature data; b) dune wavelength (L_w) vs flow depth (H) of literature and the study rivers data. The dotted line represents the Yalin (1992) criteria; c) dune height vs wavelength referred to literature and the study rivers data. In this diagram only the data of Kostaschuk et al. (1989); Kostaschuk and Ilersich (1995); Prent and Hickin (2001) and Villard and Church (2003) were used.

moving dunes. In principles, the resuspension of sand grains induced by the dunes should increase with the increase in flow velocity and depth. Nevertheless, the lack of evident changes of bedload D_{50} and D_{90} with increasing discharge and the small fraction (less than 10 %) of fine and very fine sand in the suspended load samples (collected by a US DH-59 depth integrating sampler) seems to contradict the assumption of large bed material contributions to suspended load (Church, 2006) in sand bed rivers. A possible explanation to this apparent inconsistency may stand in the capability of the Helley-Smith sampler to capture also a significant proportion of the suspended bed material, which is likely enhanced by the very flat aspect ratio of the dunes and the very low Froude numbers calculated, especially for the lower floods. The suspended fine sand supply to the beach was not investigated further, because fine sand is commonly unable to provide any significant contribution to the beach stability as fine sand grains are easily washed away and are often neglected in littoral sediment budget investigation to design beach erosion countermeasures (Hansona et al., 2002; Udo and Yamawaki, 2006; Silva et al., 2009; Osborne, 2018; McFall, 2019; Bitan and Zviely, 2020).

The movement of large sand waves, whose existence was shown in a laboratory flume experiment by Lisle et al. (1997) and in the field (Lisle, 2007) may be another factor of sediment supply variability. The bathymetric profiles surveyed in the study rivers, apparently show the occurrence of sediment waves, whose wavelength is about 10 channel widths. The processing of these data, however, is still in progress. The downstream movement of such long sand waves may alter the sediment supply to the measuring site in two ways. These streambed undulations may act as both sediment traps and sources, whereas the transit of the interweaves trough at the measuring site may significantly reduce the quantity of the moving bedload, which is mostly in suspension for the local turbulence and the higher shear stress.

The data suggest that, during the higher floods, the flow is more powerful and capable to entrain and transport bedload, irrespective of the supply from upstream. More sand is transported in suspension and the mixing effect of turbulence minimize the difference between the throughs and humps of both the small- and large-scale sand waves.

In order to qualitatively assess if the bedload flux of the study rivers reflects sediment supply conditions, the unit bedload transport rates measured in the Fiumi Uniti was compared with flume and other rivers data (Fig. 9). Flume experiments on bedload transport are commonly carried out at, or close to, full saturation of the transport capacity and may represent a useful reference. Fig. 9 shows that for comparable excess unit stream power values, the bedload transport rates of the Fiumi Uniti are less than those observed in the flume experiments of Williams (1970) but comparable to those of the East Fork River and higher than those of the Clearwater river. These latter rivers have a mixed sand and fine gravel bedload, whereas in the Fiumi Uniti it is medium sand, thus attesting a small sediment supply under conditions of excess transport capacity.

A general situation of scarcity of bedload supply to the Romagna coast also emerges by comparing the bedload rates of the smaller rivers with the Reno, the largest river of the region. Though the Reno has a catchment from ten to five times larger than the study rivers and the other small rivers depicted in Fig. 1, for comparable flow discharges higher than 150 m^3s^{-1} the bedload rates of the Reno are lower than those of the smaller rivers (Fig. 11). All these results and data point at an impoverishment of the sand supply to the Romagna coast, which partly explains the serious erosions processes that have been affecting the beaches of the region in the last decades. The consciousness that the Romagna rivers are transporting very little quantities of sand to the sea is an important staple in the discussion, at land management level, about the next plans to protect the starving beaches of the area.

The grain size of bedload contribution to the sea of both the study rivers is between medium to coarse sand (D_{50} is 0.50 and 0.49 mm in the Fiumi Uniti and the Savio, respectively). However, whether this sediment contribution is sufficient or not to naturally nourish the nearby coast is still debated (Grottoli et al., 2020). Other sampling campaigns on other rivers in the area are however necessary to extend the existing database and to confirm this worrying trend.

5.2. Dune morphology and bedload prediction

Bathymetric surveys, carried out after four of the monitored floods, revealed the presence of alluvial bedforms on the streambed of the study rivers. The selected floods were characterised by a subcritical flow regime with Froude numbers ranging between 0.14 and 0.25 (Table 3), i.e. flow conditions whereby the formation of dune bedforms is expected. The dunes measured in the study rivers are flatter than those of many other natural rivers reported in the literature (e.g. Flemming, 1978; Kostaschuk et al., 1989; Prent and

Table 4
Predictive performance (r) of the dune migration method using different criteria to assess the dune celerity.

	Fiumi Uniti		Savio	
Dune celerity criterion	Mean r	Range	Mean r	Range
Snishchenko & Kopaliani (1978)	16.68	0.09–32.26	3.02	0.58–5.46
Nikora et al. (1997)	34.54	0.66–79.24	13.12	0.53–25.72
Carling et al. (2000)	3.24	0.04–6.73	1.16	0.02–2.30
Gabel (1993)	143.04	0.77–273.50	14.70	3.03–26.38

r = Q_{bm}/Q_{bd}, predictive performance in which Q_{bm} is the bedload measured in the field and Q_{bd} is the bedload predicted by the dune migration method.

Hickin, 2001; Schippa et al., 2016; Lisimenka and Kubicki, 2019; Schippa, 2020).

The flume experiments of Tuijnder et al. (2009) demonstrated that dune steepness tends to increase with increasing sediment availability and flatter dunes are associated with sediment supply-limited conditions. The same authors also observed that dunes increase in size with increasing flow depth, under alluvial conditions (transport capacity-limited conditions). The data of Tuijder et al. (2009) also indicate that, under sediment supply-limited conditions, dune height is almost not influenced by flow depth. The dunes of the study rivers range very little in height from 0.10 to 0.28 m, in spite of a wide range in flow discharges, 22-358 m^3s^{-1}, which also includes one of the largest floods measured in the last decades in the Fiumi Uniti and a flood 1.5 times bankfull flow in the Savio.

All these considerations lead to describe the dune geometry of the study rivers as typical of supply-limited conditions, confirming the poor bedload flux pointed out by the sediment transport sampling campaigns.

The field data of this study indicate that the dune migration method can return reliable predictions of bedload transport, provided reliable field data are available or an appropriate method to calculate the dune celerity is selected. The results of this study suggest that, among the formulas selected to calculate the dune celerity, the best performance is given by Carling et al. (2000) equation, which seems to provide more realistic predictions for the study rivers. This can be accounted for by the similarity between the dune steepness of our study rivers with Carling et al. (2000) dataset, though the latter was obtained from field measurements on the Rhine river, i.e. on a much larger river. In the study reach of Carling et al. (2000) sand dunes made up a patchy network migrating on a pebbly streambed. This suggests a relative scarcity of fine sediment supply from upstream. This also suggests that supply-limited conditions can be assumed for the study rivers, whose bedload transport was measured to be modest also with medium to high floods. Further field investigations on the factors controlling dune celerity are however necessary to improve the already satisfactory performance of the dune migration method to predict bedload transport in sand bed rivers.

6. Conclusions

A field study to analyse the role of the sand supply to a severely eroding coast was carried out in two rivers (Fiumi Uniti and Savio) representative of the main geo-morphological and hydrological characteristics of small rivers in Emilia-Romagna Region coastal belt in Italy. Recognizing the importance of moving bedform as a significant and interactive element of control on bedload transport, the investigation focused on the quantification of bedload transport rate by field sampling and by the dune migrations method. In the 2005–2006 and in the 2017–2020 intervals, a wide dataset of about 30 floods were measured and the following main results were obtained:

1 In the study rivers, flow discharge is the best predictor of bedload transport. A wide range of flood flows were measured demonstrating the presence of appreciable bedload transport even though sporadically. The field measurements of bedload and the dune geometry confirmed a permanent supply-limited condition. The sandy sediment delivered by the study rivers to the Romagna coast is small compared with other rivers in other parts of the planet and even with flume experiments. This result contributes to uncover an important negative factor in the sediment budget and helps to explain the worrying beach retreat that has been affecting the Romagna coast in the last decades. It also provides a scientifically based information for planning appropriate mitigations measures.
2 Two significant ($p < 0.01$) interpolation equations (eqs. 3 and 4) were obtained to predict unit bedload transport from unit discharge of the study rivers.
3 Bedload is highly variable and poorly correlated with discharges for flows less than bankfull stage. By contrast, for discharges higher than bankfull, flow controls 81 % of bedload variability.
4 Previous studies on rivers in the Romagna region showed that the Modified Meyer-Peter and Muller (1948) and the Martin (2003) equations return the best prediction of bedload transport. This study confirmed that Martin (2003) equation provided the best performance with a discrepancy ratio of 1.65 in the Fiumi Uniti and of 16.7 in the Savio but with a determination coefficient $R^2 = 0.74$. The simple bedload equations obtained in this study and Martin (2003) equation can be used for a preliminary, though approximate, assessment of the bedload in other rivers of the Romagna coast. Though these rivers have a sand bed with dune bed forms, only 10 % of suspended load consists of fine and very fine sand. This allows to consider the bedload data measured in the field as a good approximation of the real bedload transport of the study rives.
5 For comparable flow discharges a few small rivers proved to have higher bedload rates than the Reno river, the largest of Romagna, the catchment of which is from five to ten times larger than that of the small rivers. The comparison with the bedload transport of similar rivers in the world indicates that also the bedload flux of the small rivers in the study area is rather small and it can be considered as an important factor in the severe erosion processes recorded in the Romagna coast.
6 The dune steepness, the flow depth to dune height and wavelength ratios of the monitored dune confirm that the study rivers bedforms are flatter than those observed in other rivers and flume experiments. The geometry of the monitored dunes, though similar to those from the literature, has distinctive characteristics that are supposed to result from sediment supply-limited conditions. This result confirms the general reduction of sediment supply to the Romagna beaches.
7 The study confirmed that the dune migration method in an acceptable alternative to field sampling of bedload transport. A comparison between field data and prediction by the dune migration method, using different equations to calculate the dune celerity, showed that the best predictions were obtained using Carling et al. (2000) equation. The discrepancy factor (measured to predicted bedload transport ratio) is 3.34 and 1.16 in the Fiumi Uniti and Savio rivers, respectively.

This study pointed out the importance of bedload field measurements in contributing to understand the sediment unbalance of eroding beaches and, thus, in suggesting a more comprehensive approach in the beach stabilization intervention.

Author statement

The authors' contributions to the paper were the following ones: SC: fieldwork investigation, data curation and analysis and writing of the first draft of the paper; PB: conceptualisation, methodology, data analysis, writing and editing; LS: supervision, data analysis and validation and paper editing; EG: the fieldwork activities and paper editing; PC: funds acquisition, research coordination and manuscript editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100894.

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