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Paolo Billi [(1,2)]

HOW MUCH SAND IS THERE IN THE RIVERBEDS OF TUSCANY, ITALY? FOURTY YEARS OF OBSERVATIONS

Abstract - P. Billi, *How much sand is there in the riverbeds of Tuscany, Italy? Fourty years of observations.*

In the last four decades, the beaches of Tuscany have been subjected to severe erosion processes with worrying coastline retreats. Among the main causes of such beach reduction, coastal geomorphologists have indicated a marked decrease in river sand supply. Aiming at contributing to the understanding of this problem, 36 rivers were selected and 137 samples of subsurface bed material samples were collected. The data analyses indicate a rather low content of sand (around 17%) in most of the rivers considered, except for the downstream reaches of the rivers entering the Tyrrhenian Sea. Bedload field measurements carried out on the Ombrone River revealed a high transport efficiency compared to a poor sediment supply, confirming the sediment supply limited condition of this river. Other factors and processes, such as the migration of dune bedforms and the formation and movement of large bedload waves, are considered additional factors to be considered for untangling the complexity of the sediment flux to beaches.

Key words - sand content, bedload, sediment supply, unit stream power, sediment waves, Tuscany, Italy

Riassunto - P. Billi, *Quanta sabbia c'è negli alvei fluviali della Toscana, Italia? Quaranta anni di osservazioni.*

Negli ultimi quattro decenni, le spiagge della Toscana sono andate soggette a severi processi di erosione con preoccupanti arretramenti della linea di riva. Tra le cause principali di tale riduzione dell'ampiezza delle spiagge, i geomorfologi costieri hanno indicato la riduzione di alimentazione di sabbia da parte dei fiumi. Con l'obiettivo di contribuire alla comprensione di questo fenomeno, sono stati selezionati 36 corsi d'acqua e sono stati prelevati 137 campioni di sedimenti subsuperficiali. L'analisi dei dati ha dimostrato un basso contenuto di sabbia (circa 17%) nella maggior parte degli alvei considerati, ad eccezione dei tratti terminali prefociali dei fiumi che sboccano nel Mar Tirreno. Misure di campagna del trasporto solido al fondo e in sospensione condotte sul Fiume Ombrone hanno rivelato una alta efficienza di trasporto di questo fiume a fronte di una alimentazione dei sedimenti che appare piuttosto bassa, confermando le condizioni di limitazione di alimentazione già evidenziate dai campioni d'alveo. Altri fattori come la migrazione delle dune e la formazione ed il transito di grandi onde di sedimento al fondo sono prese in considerazione come fattori addizionali che vanno approfonditi per comprendere la complessità del flusso di sedimenti verso le spiagge.

Parole chiave - contenuto in sabbia, trasporto al fondo, alimentazione dei sedimenti, potenza specifica, onde di sedimento, Toscana, Italy

Introduction

In the last five decades, the beaches of Tuscany have experienced severe erosion problems. Beach retreats ranged from 10 to 20 m per year (Cipriani *et al.*, 2001; Bini *et al.*, 2008; Guarducci *et al.*, 2011; Cipriani & Pranzini, 2014; Casarosa, 2016; Luppichi & Bini, 2025). Beaches hold a high environmental and biodiversity value and must be protected anyway. The beaches of Tuscany also have an important economic value associated with the tourist industry that results in an essential income for this region. The reduction of the beach extension translated into the loss of substantial financial resources that must be summed up to the conspicuous costs of beach defence works implemented in a still unsatisfactory attempt to contrast beach degradation.

The retreat of Tuscany beaches results mainly from a reduction of sediment supply from rivers (Pranzini, 2001; Monti & Rapetti, 2011; Diodato *et al.*, 2021 Luppichini *et al.*, 2024), the trapping and/or offshore dispersion effect of harbours, newly constructed touristic ports and other coastal infrastructures (Anfuso *et al.*, 2011). Different solutions have been proposed and implemented from rigid defences such as sea walls, rubble mound seawalls, and detached breakwaters made of gigantic boulders (Aminti & Billi, 1984), submerged groins (Aminti *et al.*, 2004), to artificial (man-controlled) beach nourishment, sand pipes and so on. Recently, following the pressure from the general public aiming at restoring and improving the environmental quality of the beaches and the unsatisfactory results obtained by the solutions adopted so far, the debate about the possibility of restoring or increasing the current flux of river sediment has arisen among scientists and local environmental authorities.

Rivers are the natural providers of the sediment that sea waves and currents redistribute longshore to maintain the beaches in an endless dynamic equilibrium between shoreline advance and retreat. In an ideal river system, of the sediment supplied to the main channel, part of the suspended load (the finer fraction) is

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deposited on the floodplain, part of the bedload is deposited in the channel (bars) and the largest proportion of the sediment (both bedload and suspended load) is transferred to the sea. Under natural conditions, though the annual sediment flux varies in response to the amount and intensity of rainfall, the shape of the flow duration curve and the effectiveness of the weathering processes on the watershed slopes, in the long term, a certain equilibrium between incoming and outgoing sediment is achieved, provided external factors such as tectonic stability, climate and land use do not change.
Since the beginning of the XIX century, several Tuscany rivers have been subjected to marked changes, even of opposite sign, such as land use change, expansion and contraction of agriculture, reforestation, river damming, industrial exploitation of river bed material, construction of embankments and other infrastructures (Agnelli *et al.*, 1998; Rinaldi *et al.*, 2008). These disturbances have altered the flow of water and sediment and rivers have responded by readjusting their channel cross-section (mainly narrowing and incision – Rinaldi & Simon, 1998; Rinaldi, 2003; Rinaldi *et al.*, 2008), changing their pattern (where the channel morphology was not fixed by rigid flow containment structures such artificial levee – Billi & Bartholdy, 2024) and reducing the in-channel storage of sediment. Ultimately, this gross imbalance resulted in a marked reduction of sediment flux and supply of sand to the beaches.
The idea of re-establishing a consistent river sediment flux to the Tyrrhenian Sea beaches is fascinating, although the complexity of the technical problems envisaged in drafting such an articulated programme and its environmental and societal implications has killed this hypothesis in the bud. Still, further studies may disclose it as an interesting opportunity. In any case, the first question that practitioners and local land managers might ask themselves is about the actual quantity of sand stored/available in the streambed of the Tuscany rivers. The main aim of this study is to try to give an answer to that crucial question while driving attention to this topic.
Few papers report data on the grain size and sand fraction of riverbeds in Tuscany. This information is sparse and typically included in individual river studies (e.g., Billi & Bettazzi, 1989; Bartholdy & Billi, 2002; Billi & Paris, 2002). Data on bedload transport based on field measurements are even less and more dispersed, except for the Ombrone River whose bedload transport has been measured in a specific three-year monitoring programme (Billi & Paris, 2004; Billi & Paris, 2014). In this framework of river sediment data scarcity, the investigation on the sand fraction in the streambed of 36 Tuscany rivers reported in this paper may represent a baseline, a reference for future studies on sediment flux to beaches, riverine biota and ecosystems, other than to provide a comprehensive picture of the sand fraction distribution in the rivers of the region.

Study area

In Tuscany, six main river systems flow into the Tyrrhenian Sea: the Arno, Ombrone, Serchio, Cecina, Albegna and Magra (Fig. 1). The largest part of the latter river catchment is in Tuscany but its lower reach is in Liguria. Nevertheless, its sediment mainly supplies the beaches of northern Tuscany. The main data of the rivers considered in this study are reported in Tab. 1. A total of 36 rivers were considered and 137 sampling sites were selected to investigate the sand fraction in the streambed of a representative number of Tuscany rivers.

Figure 1. Location map of the study rivers. The numbers indicate subreaches or the smaller rivers (see also Table 1).

The majority of the study rivers have a gravel or gravelly sand bed. Only in the largest rivers the gravel to sand bed transition is a few tens of kilometres upstream of their mouth, whereas some small rivers maintain a sandy gravel bed as far as the outlet into the sea.

Data and methods

The majority of the sediment data used in this study were collected by different field sampling campaigns during a ten-year interval across the turn of the century, though some data was collected across a 40 years interval. Most of the data is unpublished, albeit some grain size frequency distribution data such as D_{50} may have been reported in some publications.
The sandy streambeds were sampled using the US BMH-60 sampler (Guy & Norman, 1970). This sampler was developed specifically for fine sediment sampling in rivers. It is hand-held or operated by a winch from a boat or a bridge. This sampler collects about 175 cc of bed material and the samples are taken across the riverbed at predetermined intervals.

Table 1 Sand content of the study rivers.

No.	River	Samples (n)	Sand portion (%)			Area (km²)
			mean	max	min	
	Arno R. basin					8111
1	Arno, Casentino	7	15.8	17.8	13.3	
2	Arno middle reach	2	7.6	10.8	4.4	
3	Arno,middle reach	1	16.1			
4	Arno lower reach	1	98.9			
5	Corsalone	4	15.6	16.8	14.5	90
6	Elsa	1	83.3			301
7	Era	1	45.4			204
8	Ombrone PT	1	26.9			247
9	Pesa	3	15.8	20.5	9.4	243
10	Sieve	11	13.9	27.0	7.0	840
11	Virginio	4	14.3	22.4	4.1	60
	Arno R. mean		*32.1*			
12	**Ombrone**	14	26.5	81.0	7.0	3680
13	Arbia	2	12.0	14.0	10.0	178
14	Farma	2	10.0	14.0	6.0	100
15	Gretano	2	20.4	25.9	15.4	74
16	Melacce	2	8.5	11.0	6.0	74
17	Maiano	2	22.0	29.0	15.0	64
18	Merse	8	16.2	21.0	5.0	483
19	Orcia	7	13.0	20.0	5.0	351
20	Trasubbie	2	15.0	19.0	11.0	110
	Ombrone R. mean		*16.0*			
21	**Serchio**	11	16.1	27.0	8.0	1435
22	Lima	4	13.0	15.0	11.0	214
23	Turrite Gallicano	1	10.0			43
24	Turrite Secca	1	10.0			79
	Serchio R. mean		*12.3*			
25	**Cecina**	12	21.7	27.1	14.9	904
26	Botra	2	26.1	29.1	23.0	
27	Lopia	2	16.9	17.6	16.3	
28	Sterza	4	14.7	19.8	12.3	
	Cecina R. mean		*19.9*			
29	**Albegna**	10	14.4	23.9	8.4	748
30	Bruna	2	26.5	42.0	11.0	552
31	Camaiore	2	20.4	33.0	7.8	57
32	Carrione	1	22.1			53
33	Cornia	4	11.1	13.7	5.5	419
34	Fine	1	50.6			123
35	Frigido	2	12.4	13.6	11.1	63
36	Magra	1	18.6			1686
	Overall mean		*17.6*			

For sampling gravel bed rivers, the volumetric method (Bunte & Abt, 2001) was used. It consists of collecting a pre-defined volume of sediment such that the weight of the largest stone is equivalent to 5-10% of the whole sample (Church *et al.*, 1987). To obtain representative samples, it is crucial to select river reaches that are as close as possible to the natural hydraulic conditions, that is far, at least ten channel widths upstream or downstream, from any artificial disturbance (weir, masonry embankments, diversions, bridges, etc.). The selected river reach is divided into three sectors, upstream, middle and downstream, and, in the centre of each sector, an imaginary or physical line is traced transverse to the flow. Along this line, three equidistant samples are taken on the left, middle and right side (Fig. 2).

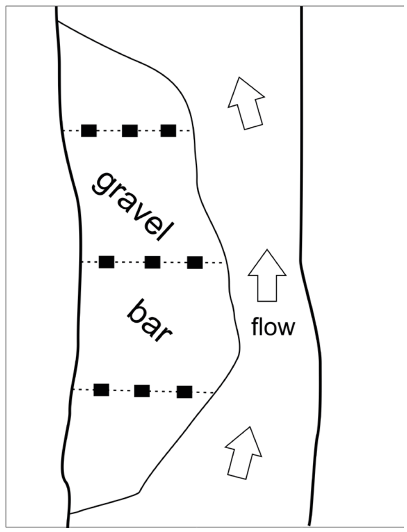

Figure 2. Subsurface bed material sampling scheme. The black squares are the points of subsample sediment collection (see also figure 4). The nine subsamples are then combined to form the representative sample of a specific site.

In some reaches, the streambed may be armoured, that is the surface consists of a concentration of coarser particles (Fig. 3). The streambed armouring is typically generated by the winnowing of the finer particles, particularly in the flood-receding phase. Some authors have reported that a 'static armour' forms in degrading beds, under conditions of supply limited conditions (Gomez, 1983). Typical examples are the river reaches downstream of a dam. A 'mobile' or' dynamic armour' may form in gravel rivers characterised by an appreciable sediment input through a combination of winnowing and kinematic sorting (Parker & Klingeman, 1982). Several authors (e.g., Parker & Klingeman, 1982) consider the subsurface sediment grain size distribution the closest to the bedload transported during floods and for this reason and the purpose of this study, the subsurface material is the most appropriate to investigate the sand supply.

Figure 3. Example of an armoured bed. The coarse particles are concentrated on the surface, whereas the subsurface material is distinctively finer.

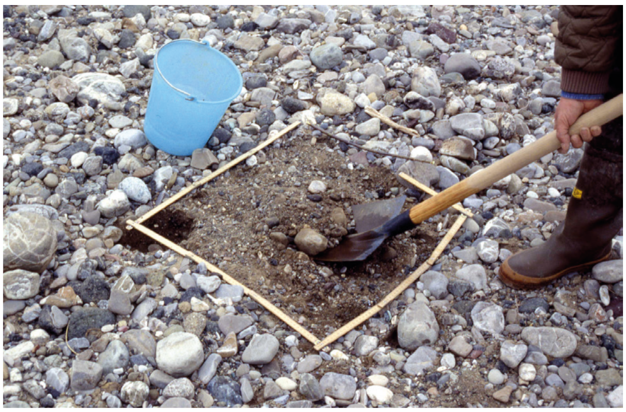

Figure 4. Collection of a subsample (black square in figure 2). Notice the armoured streambed surface and the finer sediment underneath exposed after removing the surface coarse particles.

Figure 5. The template for field sieving of the coarse particles. The holes are arranged on a ½ phi scale.

Streambed armouring is present in the study rivers, though it is not ubiquitous. For uniformity of sampling, at any sub-sampling point, the coarse particles on the surface were removed by hand and the subsurface material was shovelled into a basket (Fig. 4). The largest particles were sorted by a template with holes arranged on a ½ phi scale (Fig. 5) and weighed in the field. The finer sediment was brought to the laboratory and sieved by a Ro-Tap shaker with sieves arranged on ½ phi mesh size.

In order to analyse the role of flow energy in the sediment dynamics, the following formulas for stream power, unit stream power and shear stress were used.

Unit stream power (ω) is defined as the stream power (Ω) per unit width, that is:

$$\Omega = \rho g Q J \quad [\mathrm{W\ m}] \tag{1}$$

$$\omega = \Omega / B \quad [\mathrm{W\ m^{-2}}] \text{ equivalent to } [\mathrm{kg\ m^{-1} s^{-1}}]. \tag{2}$$

These latter units are preferred for uniformity with bedload.

$$\omega = v\tau \quad [\mathrm{kg\ m^{-1} s^{-1}}] \tag{3}$$

$$\tau = \rho g h J \quad [\mathrm{kg\ m^{-2}}] \tag{4}$$

in which ρ is the density of water; g is gravity; Q is discharge; J is the flow energy gradient generally assumed as parallel to the streambed gradient; B is channel width; v is flow velocity; τ is shear stress; h is flow depth.

RESULTS

The average quantity of sand in the streambed of Tuscany rivers is 17.6% (Tab. 1). Most rivers have small proportions of sand along their entire course, especially if they are tributaries of larger rivers. Almost all the rivers that flow into the Tyrrhenian Sea have a predominantly sand bed, whose length scales with the size of the catchment, that is from ten to 50 km upstream of the mouth. Exceptions are the the small rivers whose headwaters are very close to the coastline such as the Frigido and the Carrione.

The lower reaches store a large quantity of sand supplied from the upstream reaches through selective transport. In almost three quarters (73%) of the 137 sampling sites, the quantity of sand is less than 20%, whereas in half of the sampling sites, it is comprised between 10 and 20% (Fig. 6). These data indicate that, in the middle and upper reaches of the Tuscany rivers, the content of sand is rather scarce.

For some rivers, it is possible to analyse the downstream increase in the sand content, but the patterns are very irregular and do not follow the general exponential law that, by analogy, is expected for the decrease in grain size with distance reported in the literature (e.g., Knighton, 1988):

$$D = D_0 e^{-\alpha L} \quad [5]$$

In which D is the particle size, D_0 is the initial grain size at the distance L = 0 from source and α is a coefficient including both abrasion and sorting effect.

In the Cecina River, the increase of the sand content with decreasing distance from the mouth is exponential (Fig. 7a), though the correlation coefficient is rather low ($R^2 = 0.46$):

$$S_c = 27.908 e^{-0.012L} \quad [6]$$

The content of sand of the Ombrone is rather high in the upstream reaches, where the river drains the Pleistocene fluvial and marine sands and clays of the Siena graben, then decreases to very low values in the long gorge of the middle reach incised into Cretaceous limestones, turbiditic marlstones and limestones and Oligo-Miocene sandstones, to increase again in the terminal reach crossing the Quaternary coastal plain (Fig. 7b). The downstream variation in the sand content of the Merse River shows a segmented pattern (Fig. 7c). In the upper reach, the river crosses the Chiusdino graben filled with Pliocene sands and Quaternary lacustrine deposits and the sand content tends to increase downstream. Then, the river flows through a narrow gorge cut into Carboniferous to Triassic quartzites, shists and limestones and the sand content decreases to very low values in a very coarse-grained streambed. Downstream of the gorge, the sand fraction increases again in the alluvial plain before joining the Ombrone R. (Fig. 7c). In the Orcia R., the pattern of the sand percentage variation is definitely unexpected. The quantity of sand tends to decrease downstream (Fig. 7d) and this is difficult to explain because, except for the middle reaches incised into Cretaceous limestones and marlstones,

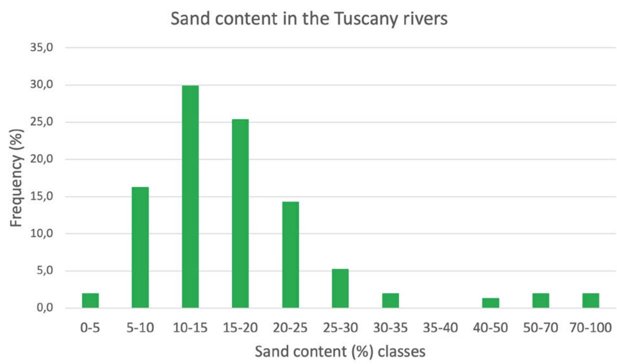

Figure 6. Frequency distribution of the sand content classes in the riverbeds of Tuscany.

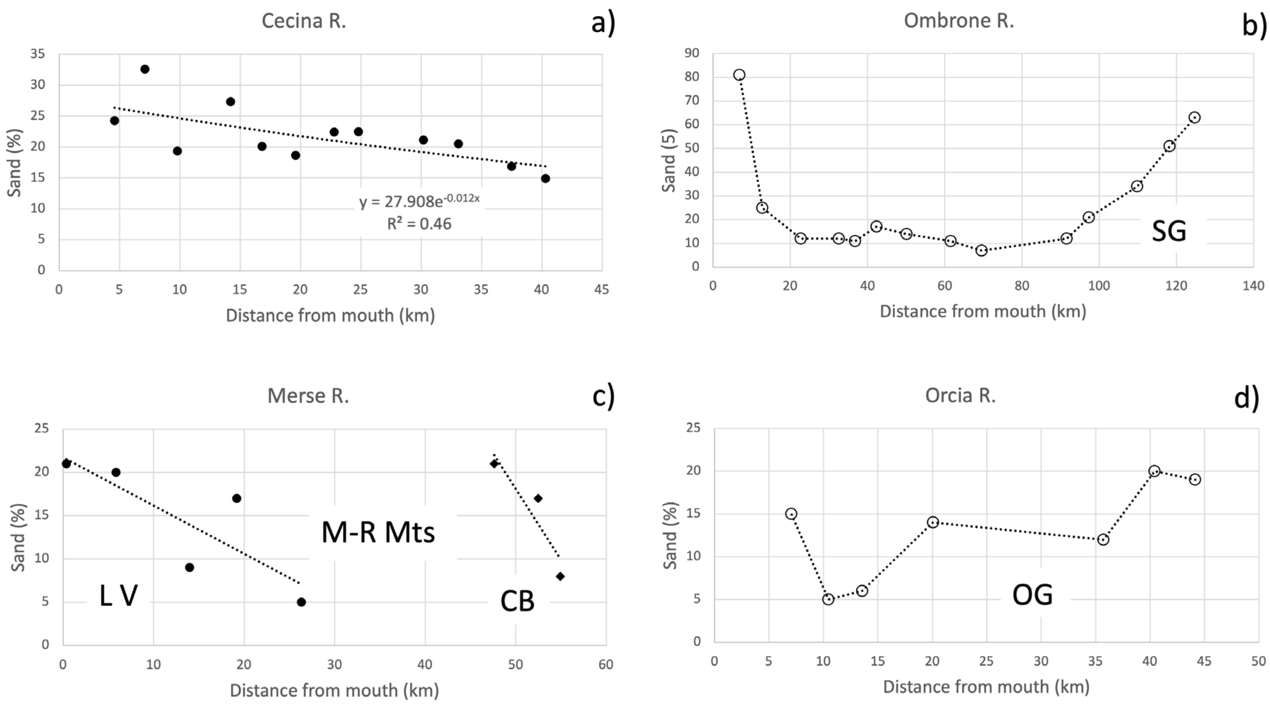

Figure 7. Variation of the sand content with the distance from the mouth or confluence into the main river. SG = Siena Graben; CB = Chiusdino Basin; M-R MTS = Monticiano-Roccastrada mountains; LV = lower valley; OG = Orcia Gorge.

where no sample was collected, the river flows on Pleistocene, unconsolidated marine and fluvial deposits. In the lower reaches, from the exit of the gorge to the confluence with the Ombrone, the Orcia maintains a relatively high streambed gradient of 0.0044, which is slightly higher than that of the reach upstream of the gorge (0.0042), but one order of magnitude gentler than that in the gorge (0.014). These examples suggest the importance of the bedrock mechanical characteristics, not only in terms of resistance to the weathering and erosion processes but also in controlling the river channel morphology and gradient. River channels cut into hard rocks tend to be steeper and the excess flow energy may be capable of flushing downstream the greatest proportion of the fine particles supply.

Other rivers with five or more sampling sites evenly distributed along the main stem (Sieve, Arno Casentino, Serchio, Cornia, Albegna do not show any distinctive downstream trend in the streambed sand content, which revolves around low values of 13-16%.

The flux of sandy sediment to the beaches is not only influenced by the sediment supply but also by the river flow sediment transport capacity. The sediment supply to a given reach consists, at least, of four main components: 1) the product of weathering and erosion processes on slopes; 2) the bedload contribution from upstream tributaries; 3) bank erosion; 4) the sediment entrained from upstream reaches of the control section, especially if the streambed is armoured and the fine sediment is entrained when the flow is capable of breaking the armour layer.

Field measurements of bedload transport carried out during floods of the Ombrone River at the Istia d'Ombrone monitoring station (Billi & Paris, 2004) provide an interesting insight into the flux of sand in gravel-bed rivers. Bedload transport was measured with a Helley-Smith bedload sampler (Helley & Smith, 1971) and flow depth and velocity were also measured before any bedload sampling at any measuring vertical. The data indicate that an appreciable quantity of bedload could be collected for unit stream power values as low as 0.68 kg $m^{-1}s^{-1}$ (Fig. 8).

Fig. 8 shows that as unit stream power increases the percentage of sand tends to decrease because the flow energy is capable of entraining also coarse particles such as gravel and granules. This unbalance is only apparent because, as Fig. 9 shows, the total volume of sand is expected to exponentially increase with increasing unit stream power. From Fig. 9 it is possible to assess that with a unit stream power of 1 kg $m^{-1}s^{-1}$, if the bedload is 100% sand, the sand flux is about 1 t/day. With a unit stream power of 8 kg $m^{-1}s^{-1}$, even if the sand content is only 50% the transport rate is 5 t/day. This result is corroborated by the comparison between the grain-size distribution of the bedload samples and that of the streambed of the Ombrone River at Istia (Fig. 10). Fig. 10 shows clearly that bed material grain size distribution is rather different from that of the transported bedload and evident changes are mainly due to variations in the coarser fractions.

Aiming at investigating transport efficiency, expressed as the proportion of the available flow power being used in bedload transport, Bagnold (1973) proposed the following equation:

$$E_b = 100 i_b / (\omega / \tan \alpha) \qquad [7]$$

in which E_b is the transport efficiency index, i_b is the unit transport rate, ω is unit stream power and α is the angle of internal friction, assumed constant at 0.63.

Reid & Laronne (1995) plotted the bedload data of different rivers for comparison and traced selected levels of Bagnold transport efficiency (their figure 3). The bedload data of the Ombrone River were plotted on the same diagram as well (Fig. 11) and the transport efficiency of this river is around 30% and tends to increase as unit stream power increases. This result indicates that the Ombrone transport capacity is higher than the sediment supply from upstream. In other words, the sediment supply to the main channel is substantially less than the amount that the river would be capable of transporting. The reasons for a reduced sediment supply are manifold and affect many rivers in Tuscany and other Italian Regions (see Rinaldi, 2003; Preciso *et al*., 2012; Billi & Bartholdy, 2004).

The bedload variability of the Ombrone is significantly (95%) explained by discharge (Fig. 12) and can be expressed by the following equation:

$$Q_b = 0.0005 Q^{2.4577} \qquad [8]$$

in which Q_b is bedload transport rate in t/day and Q is flow discharge in m^3s^{-1}.

The bedload transport data of the Ombrone were measured during lower than, close to and at bankfull flow. It is known from the literature (e.g. Knighton, 1998) that bankfull flow (typically the flow with 1.58-2.33 years return time) coincides with the dominant discharge, i.e. the discharge that in the long term controls the river channel morphology and that transport the largest quantity of bedload. Nevertheless, further field measurements would be desirable for corroborating the validity of Fig. 12 correlation equation (8) for sediment flux predictions.

The suspended sediment load is also well correlated with discharge (R^2 = 0.99) (Fig. 12) through the following equation:

$$Q_s = 0.5967 Q^{2.1417} \qquad [9]$$

in which Q_s is suspended load transport in t/day and Q is flow discharge in m^3s^{-1}.

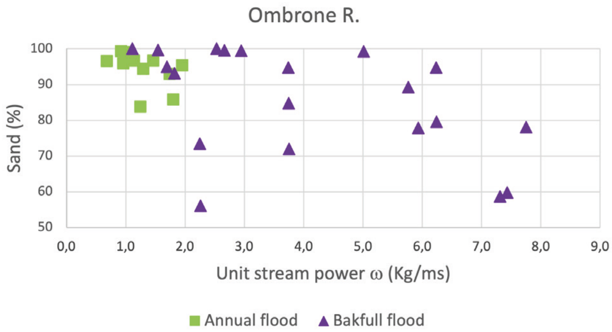

Figure 8. Plot diagram of unit stream power (ω) and sand percentage in the bedload transport samples.

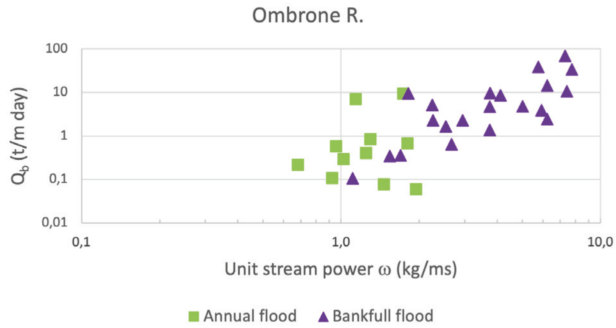

Figure 9. Variation of bedload transport (Q_b) with unit stream power (ω).

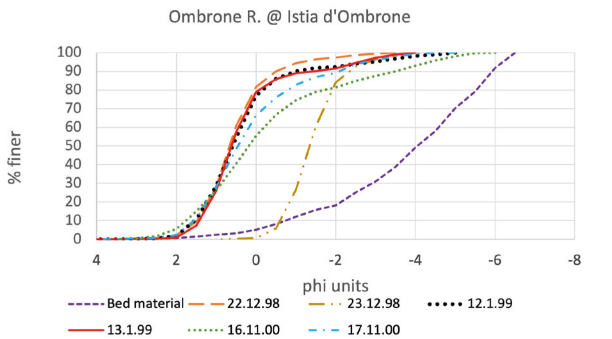

Figure 10. Comparison between the grain size distribution of bed material and composite bedload transport samples collected during monitored floods.

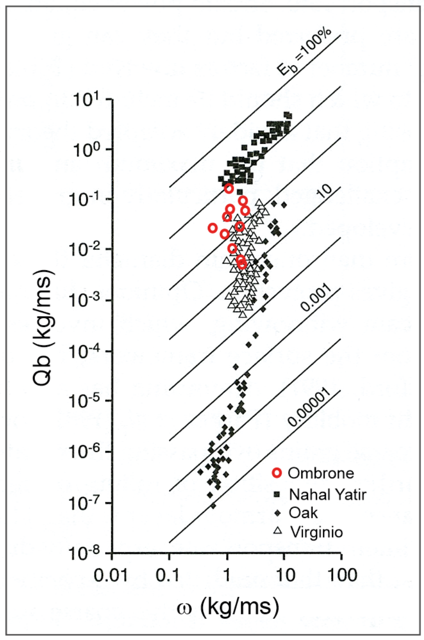

Figure 11. Plot diagram of bedload transport rate (Qb) vs unit stream power (ω). The Ombrone R. data are compared with other river data from the literature (Laronne & Reid, 1995). The Ombrone R. data plot close to the Virginio River, another Tuscany stream. The efficiency of the Ombrone R. is around 30%.

It is worth noticing that both bedload and suspended load tend to vary approximately with the square of discharge and though the interpolating lines of bedload and suspended load are almost parallel, the bedload yield is about three orders of magnitude lower than the suspended sediment yield. The proportion of bedload to suspended load is highly variable, but in the lower reaches, at the transition from gravel to sand bed, bedload is typically in the 1-5% range (e.g., Babinski, 2005). The grain size analyses of a few suspended sediment samples of the Ombrone River revealed no sand content and a medium to coarse silt composition. In gravel bed rivers, however, even in their downstream reaches, suspended load commonly includes a fine to very fine sand fraction in the 1-10% range (e.g., Walling & Moorehead, 1989).

The data analysed so far indicate a general condition of limited sediment supply, the downstream transfer of the sand component and its accumulation in the coastal reaches. Here, though the sediment flux associated with floods of different magnitudes may be a conspicuous part of the sand supply to the beaches, another important contribution may be found in the dune bedforms migration. The bedload measure-

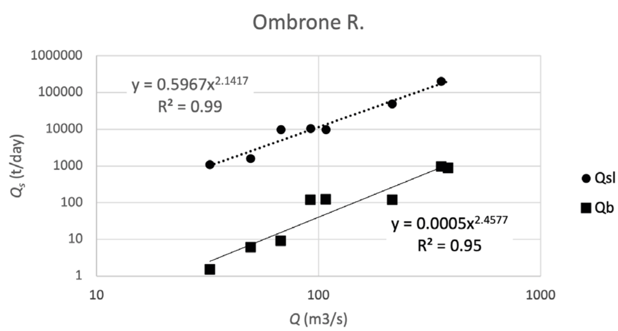

Figure 12. Variation of sediment transport (Q_s) with flow discharge (Q). Qsl = suspended sediment transport; Qb = bedload transport.

ments of the Ombrone River indicate that an appreciable quantity of bedload was collected by the Helley-Smith sampler with a flow velocity as low as 0.45 ms^{-1} and a unit stream power of 0.68 kg $m^{-1}s^{-1}$. Below these values and especially if dune bedforms are present on the streambed, the efficiency of the Helley-Smith bedload sampler decreases for the difficulty to operate in the correct horizontal position. Laboratory experiments (e.g., Southard & Boguchwal, 1990; Best, 1996) have demonstrated that ripples and dunes bedforms do form with flow velocity and unit stream power lower than those observed in the Ombrone. Dune height, wavelength and migration celerity are substantially influenced by flow depth and velocity. This implies that both ripples and dunes may move downstream also during the receding flood phase or even lower flows. Though the six-rule introduced by Yalin (1992), whereby dune wavelength and height are about six times and one-sixth of flow depth, respectively, is seldom verified in the field, and taking as a reference dune steepness ratio (dune height/dune length) of 0.021 as measured by Billi *et al.* (2017) in the coastal reach of a couple rivers in Romagna, dunes 0.5 m high and 20-25 m long are expected to form, migrate downstream and, hence, provide the beaches with an important contribution of sand. The field investigation on the relationship between dune migration and sediment supply to the beaches is still in its infancy in Italy, but further studies could provide important insights into the beach sediment budget.

Discussion

The quantity of sand in a river bed depends on many factors including sediment supply, intensity and duration of the last flood before sampling, channel storage capacity, channel morphology, bedrock lithology, climate, etc. The content of sand in a riverbed is, however, a matter of fact, even if it is not enough to determine the sediment flux. The sand content can be seen as a partial indicator of the sand supply that has been trapped in the streambed and of the sediment supply status of a river system. In some of the study rivers, the bed material samples collected are very few and this is an actual limitation of this study. The sand content of these rivers, however, is very close to the average percentage of larger river systems with many more samples. The only way to fill this gap of knowledge stands in a new large-scale sampling campaign that, hopefully, could be carried out in the future.

The understanding of sand flux and trapping pattern is complicated by the variability of flow and sediment supply, entrainment and trapping processes. Unpublished data of repeated bed material sampling across three years at 12 sites in the Cecina River show that subsurface material has the highest average content of sand (21.7%) followed by pools (20.0%), bar surface (18.6%) and riffles (8.2%). The grain size data of these three sampling campaigns indicate that the sand content in the subsurface material is the least variable in time, with the difference between the highest and lowest value S_v = 2.9%, whereas the most variable is the pools with S_v = 12.0% followed by the bar surface with S_v = 11.2% and riffles with S_v = 4.1%. These results confirm that the measurement of subsurface sand content is a reliable method in an attempt to represent the quantity of sand in a streambed. The Cecina R. data, however, highlight the complexity of the sand flux controlled by locally variable processes of entrainment, transport and entrapment. The repeated field observations on the sediment dynamics in the Cecina R. revealed that pools are subjected to cycles of scouring and fine sediment (mainly sand) filling. The pools are the deepest part of a gravel bed river and during high flood experience high shear stress capable of scouring even a coarse gravel bed, as predicted by the velocity (or shear stress) reversal theory proposed by Keller (1971) and confirmed by additional field observations and measurement by Carling (1991). Pools are typical hydromorphic units that punctuate the channel of gravel bed rivers and, though the amount of sediment entrapped during the receding flood phase is variable, commonly, it is not enough to fill and, therefore, to erase the pool itself. The field observations on the Cecina R. demonstrated that some deep pools were completely filled (they were not recognizable without an established reference) and then scoured again during the next flood.

Some authors (e.g., Madej & Ozaki, 1996; Lisle *et al.*, 1997, 2001) have supposed the existence of sediment waves that move downstream and that could be responsible for bedload pulses measured in the field by a few authors (e.g., Reid & Frostick, 1986; Tacconi & Billi, 1987; Preciso *et al.*, 2012) and, likely, for the cycles of scour and fill in the pools. Bathymetric data surveyed in the downstream reach of two small streams in Romagna (Cilli *et al.*, 2021) pointed out the occurrence of sediment waves a few decimetres thick at the front and about 40 channel widths long.

The pool scouring and filling mechanism and the formation and movement of the sediment waves are poorly known and deserve to be further explored. These processes, however, add other elements of complexity to the understanding of the variability of sand flux and supply to the river mouth and then to the beaches.

Concluding remarks

This study investigated the quantity of sand present in the streambed of 36 rivers in Tuscany, Italy. For this purpose, 137 subsurface bed material samples were collected in about 10 years around the turn of the century (though for a few rivers it spanned about 40 years). The data obtained were compared with the bedload field measurements carried out from 1999 to 2001 on the Ombrone River and other field observations of bedload wave dynamics in the Cecina River. The data analyses lead to the following main conclusions:

1. Most of the study rivers have a gravel bed for their whole length. Only the most downstream reaches of the rivers entering the Tyrrhenian Sea and a few of their tributaries have a sandy streambed. The average sand content of all the study rivers is rather low, 17.6%, whereas that of the gravel reaches is 16.1%.
2. The poor percentage of sand in the rivers of Tuscany is likely a response to the reduction of sediment supply caused by land use change and the channel morphology changes induced by the industrial exploitation of bed material, the construction of dams and artificial embankments.
3. Bedrock has some influence on the river bed sand content. River reaches crossing Quaternary structural basins or Pleistocene marine deposits have a sand quantity almost twice that of the rivers flowing through gorges cut into bedrock. In rivers without strong structural and lithological discontinuity, such as the Cecina River, the sand content increases exponentially down valley as expressed by eq. (2).
4. The bedload field measurements on the Ombrone River demonstrate that its transport capacity is in excess of the sediment supply and, though the bedload transport rate is significantly controlled by flow discharge (see eq. 8), bedload yield is three orders of magnitude lower than suspended sediment yield.
5. For a better understanding of the sand supply and flux to beaches other factors and processes such as the occurrence of migrating bedforms during low flows and the formation and downstream movement of channel scale bedload waves should be investigated in different rivers.

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Conflict of interest statement

The author declares that he has no conflict of interest neither known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Agnelli A., Billi P., Canuti P., Rinaldi M., 1998. *Dinamica morfologica recente dell'alveo del Fiume Arno*. CNR-GNDCI Pubblicazione n. 1739, Pacini Editore, Pisa.

Aminti, P., Billi, P., 1984. *An investigation of the effects of breakwaters on beach sediment characteristics.* Catena 11: 391-400.

Aminti P., Cammelli C., Cappietti L., Jackson N.L., Nordstrom K.F., Pranzini E., (2004). *Evaluation of beach response to submerged groin construction at marina di ronchi, italy, using field data and a numerical simulation model.* Journal of Coastal Research 33: 99-120.

Anfuso G., Pranzini E., Vitale G., 2011. *An integrated approach to coastal erosion problems in northern Tuscany (Italy): Littoral morphological evolution and cell distribution*. Geomorphology 129: 204-214.

Babinski Z., 2005. *The relationship between suspended and bed load transport in river channels.* In: Walling D.E., Horowitz A.J. (eds), Sediment Budgets: 182-188. IAHS Publ. 291.

Bagnold R.A., 1973. *The nature of saltation and of "bedload" transport in water.* Proceedings of the Royal Society, London, A 332: 473-504.

Bartholdy J., Billi P., 2002. *Morphodynamics of a pseudomeandering gravel bar reach.* Geomorphology 42: 293-310.

Best J.L., 1996. *The fluid dynamics of small-scale alluvial bedforms.* In: Carling P.A., Dawson M. (eds), Advances in Fluvial Dynmaics and Stratigraphy: 67-125. Wiley, Chichester.

Billi P., Bettazzi A., 1989. *Esperienze e prospettive per una corretta metodologia di rilevamento dei dati sedimentologici di un corso d'acqua alluvionale: l'esempio del F. Orcia.* Atti del Convegno: Ingegneria del Territorio: Dati, Modelli e Tecnologie Informatiche, Firenze 1-3 giugno: 359-361.

Billi P., Paris E., 2002. *Realizzazione di un sistema di monitoraggio delle portate liquide e solide del Fiume Ombrone.* In: Teruggi L.B. (ed.), Manejo Integral de Cuencas Hidrograficas y Planificacion Territorial: 57-65. Università di Mar del Plata.

Billi P., Paris E., 2004. *Bedload transport and channel dynamics of the Ombrone River (Tuscany, central Italy*). Oral presentation abstract, 32nd International Geological Congress, Firenze 20-28 august.

Billi P., Paris E., 2014. *Gli apporti di sabbie fluviali ai litorali di Toscana e Romagna*. Primo Forum Internazionale del Mare e delle Coste, Forte dei Marmi, 25-26 settembre, relazione ad invito.

Billi P., Bartholdy J., 2024. *Human impact and channel dynamics of a low sinuosity pseudomeandering river.* Catena 239: 107895.

Billi P., Salemi E., Preciso E., Ciavola P., Armaroli C., 2017. *Field measurement of bedload in a sand-bed river supplying a sediment starving beach.* Zeitschrift für Geomorphologie 61 (3): 207-223.

Bini M., Casarosa N., Ribolini A., 2008. *L'evoluzione diacronica della linea di riva del litorale pisano (1938-2004) sulla base del confronto di immagini aeree georeferenziate.* Atti della Società Toscana di Scienze Naturali , Memorie Serie A 113: 1-12.

Bunte K., Abt S.R., 2001. *Sampling surface and subsurface particle-size distribution in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring.* General Technical Report RMRS-GTR-74, US Forest Service, Fort Collins.

CARLING P.A., 1991. *An appraisal of the velocity-reversal hypothesis for stable pool-riffle sequences in the River Severn, England*. Earth Surface Processes and Landforms 16: 19-31.

CASAROSA N., 2016. *Studio dell'evoluzione del litorale pisano tramite rilievi con GPS differenziale (2008-2014).* Studi Costieri 23: 3-20.

CHURCH M.A., MCLEAN D.G., WOLCOTT J.F., 1987. *River bed gravels: Sampling and analysis*. In: Thorne C.R., Bathurst J.C., Hey R.D. (eds), Sediment Transport in Gravel-Bed Rivers: 43-88. Wiley, New York.

CILLI S., BILLI P., SCHIPPA L., GROTTOLI E., CIAVOLA P., 2021. *Bedload transport and dune bedforms characteristics in sand-bed rivers supplying a retreating beach of the northern Adriatic Sea (Italy).* Journal of Hydrology: Regional Studies 37: 100894. https://doi.org/10.1016/j.ejrh.2021.100894

CIPRIANI L.E., FERRI S., IANNOTTA P,, PAOLIERI F., PRANZINI E., 2001. *Morfologia e dinamica dei sediemnti del litorale della Toscana settentrionale*. Studi Costieri 4: 119-156.

CIPRIANI L.E., PRANZINI E., 2014. *Beach erosion and protection in Tuscany*. Nuova Grafica Fiorentina, Firenze.

DIODATO N., CHARPENTIER LJUNGQVIST F., BELLOCCHI G., 2021. *Outcome of environmental change from historical sediment discharge in a Mediterranean fluvial basin, 1500-2019 CE*. Environmental Research Communications 3: 071002

GOMEZ B., 1983. *Temporal variations in bedload transport rate: The effect of progressive bed armouring*. Earth Surface Processes and Landforms 8 (1): 41-54.

GUARDUCCI A., KUKAVICIC M., PICCARDI M., ROMBAI L., 2011. *Linea di costa e torri di guardia in Toscana: il caso grossetano (dal XVII secolo ad oggi*. In: D'Ascenzo A. (ed.), Dalla mappa al GIS. Atti del quarto seminario di studi storico-cartografici: 187-211. Brigati, Genova.

GUY H.P., NORMAN V.W., 1970. *Field methods for Measurement of Fluvial Sediment*. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2. USGS, Washington.

HELLEY E.J., SMITH W., 1971. *Development and Calibration of a Pressure-Difference Bedload Sampler*. U.S. Geological Survey Open-File Report 8037-01, Washington.

KELLER E.A., 1971. *Areal sorting of bedload material, the hypothesis of velocity reversal*. Geological Society of America Bulletin 82: 279-280.

KNIGHTON D., 1998. *Fluvial Forms and Processes: A New Perspective*. Arnold, London.

LISLE T.E., PIZZUTO J.E., IKEDA H., ISEYA F., KODAMA. Y., 1997. *Evolution of a sediment wave in an experimental channel*. Water Resources Research 3: 1971-1981.

LISLE T.E., CUI Y., PARKER G., PIZZUTO J.E., DODD A.M., 2001. *The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers*. Earth Surface Processes and Landforms 26: 1409-1420.

LUPPICHINI M., LAZZAROTTI M., BINI, M., 2024. *Climate change as main driver of centennial decline in river sediment transport across the Mediterranean region*. Journal of Hydrology 636: 131266. https://doi.org/10.1016/j.jhydrol.2024.131266

LUPPICHINI M., BINI M., 2025. *40-Year shoreline evolution in Italy: Critical challenges in river delta regions*. Estuarine, Coastal and Shelf Science 315: 109166.

MADEJ M.A., OZAKI V., 1996. *Channel response to sediment wave propagation and movement, Redwood Creek, California, USA*. Earth Surface Processes and Landforms 21: 911-927.

MONTI S., RAPETTI F., 2011. *Stima del trasporto potenziale sul fondo del Fiume Arno (Toscana) tra il 1951 e il 2010*. Atti della Società Toscana di Scienze Naturali , Memorie Serie A 116: 115-126.

PARKER G., KLINGERMAN P.C., 1982. *On why gravel bed streams are paved*. Water Resources Research 18 (5): 1409-1423.

PRANZINI E., 2001. *Updrift river mouth migration on cuspate deltas: two examples from the coast of Tuscany (Italy).* Geomorphology 1-2: 125-132.

PRECISO E., SALEMI E., BILLI P., 2012. *Land use changes, torrent control works and sediment mining: Effects on channel morphology and sediment flux, case study of the Reno River (Northern Italy).* Hydrological Processes 26 (8): 1134-1148.

REID I., FROSTICK L.E., 1986. *Dynamics of bed load transport in Turkey Brook, a coarse-grained alluvial channel*. Earth Surface Processes and Landforms 11: 143-155.

REID I., LARONNE J.B., 1995. *Bed load sediment transport in an ephemeral stream and a comparison with seasonal and perennial counterparts*. Water Resources Research 31 (3): 773-781.

RINALDI M., 2003. *Recent channel adjustments in alluvial rivers of Tuscany, Italy*. Earth Surface Processes and Landforms 28: 587-608.

RINALDI M., SIMON A., 1998. *Bed-level adjustments in the Arno River, central Italy*. Geomorphology 22: 57-71.

RINALDI M., TERUGGI L.B., SIMONCINI C., NARDI L., 2008. *Dinamica recente ed attuale di alvei fluviali: alcuni casi di studio appenninici (Italia centro-settentrionale).* Il Quaternario. Italian Journal of Quaternary Sciences 21 (1B): 291-302.

SOUTHARD J.B., BOGUCHWAL L.A., 1990. *Bed configurations in steady unidirectional water flows. Part 2. Synthesis of flume data.* Journal of Sedimentary Petrology 60 (5): 658-679.

TACCONI P., BILLI P., 1987. *Bedload transport measurements by the vortex-tube trap on Virginio creek, Italy*. In: Thorne C.R., Hey R.D., Bathurst J.C. (eds), Problems of Sediment Transport in Gravel-Bed Rivers: 358-616. Wiley, New York.

WALLING D.E., MOREHEAD P.W., 1989. *The particle size characteristics of fluvial suspended sediment: an overview*. In: Sly P.G., Hart B.T. (eds), Sediment/Water Interaction. Hydrobiologia, 176/177: 125-149.

YALIN M.S., 1992. *River mechanics*. Pergamon, Oxford, 219 pp.

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