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Paolo Billi [(*)]

QUANTIFICATION OF BEDLOAD FLUX TO BEACHES WITHIN A GLOBAL CHANGE PERSPECTIVE

Abstract - P. Billi, *Quantification of bedload flux to beaches within a global change perspective.*

During the last five decades many beaches in Italy, as well as in many other industrialized countries, underwent severe erosion processes. Though many efforts have been deployed by coastal authorities and local administrations, many touristic beaches have disappeared or remarkably reduced their width. The sand supply from adjacent rivers is one of the most important factors of beach equilibrium, but in recent decades it decreased substantially. The problem of bedload flux quantification is analyzed and some field data are compared with empirical or physically based models. The results indicate a very poor performance of bedload equations and a common sediment supply limited condition for a few studied rivers in the Northern Apennines. The reason for such a scarcity of bedload yield are discussed. The field data are also used to describe the pattern of sediment supply during the recent decades; trend lines of both sediment and characteristic discharges are obtained to depict (worrying) future scenarios of beach degradation.

Key words - bedload, beach erosion, sediment supply, bankfull discharge, suspended load, climate change

Riassunto - P. Billi, *Stima degli apporti solidi fluviali alle spiagge in una prospettiva di cambiamento globale.*

Durante gli ultimi cinque decenni, molte spiagge italiane, cosí come in molte altri paesi industrializzati, sono andate soggette a gravi problemi di erosione. Sebbene molti sforzi siano stati fatti dalle autorità costiere e dalle amministrazioni locali, molte spiagge turistiche sono scomparse o hanno ridotto sensibilmente la loro ampiezza. L'alimentazione di sabbia da parte dei fiumi è uno dei più importanti fattori di equilibrio di una spiaggia, ma nei decenni recenti questi apporti si sono ridotti di molto. In questo lavoro viene presentata un'analisi del problema della quantificazione del trasporto al fondo e viene presentato un confronto tra i dati di campagna e le stime di modelli empirici e fisicamenet basati. I risultati indicano una scarsa affidabilità delle equazioni di trasorto al fondo e la presenza di condizioni di scarsa alimentazione da monte per alcuni fiumi dell'Appenino settentrioanle. Le ragioni di tale scarsità di apporti solidi di fondo vengono analizzate e discusse. I dati di campagna sono stati utilizzati anche per descrivere l'andamento degli apporti solidi durante gli ultimi decenni. Sono state inoltre derivate le linee di tendenza sia degli apporti solidi che di portate caratteristiche al fine di delineare (preoccupanti) scenari futuri di degrado delle spiagge.

Parole chiave - trasporto al fondo, erosione di spiaggia, alimentazione di sedimenti, portata ad alveo pieno, trasporto in sospensione, cambiamento climatico

1. Introduction

Fluvial systems make up the natural network through which sediment transfer from slopes to depositional area, such as alluvial plains and beaches, takes place. The amount of sand released by a river at its mouth is the result of complex hydrological and hydraulic processes that interact with the geomorphological dynamics of the watershed; moreover, it is also influenced by the presence of several human activities. The understanding of such phenomena is crucial for a sound beach management: both for touristic exploitation and for its environmental values protection. In this regard, a key step is to achieve an adequate knowledge of the space and time distribution of the river sediment yield. During the last decades, beach erosion has been a main concern for very many public administrations in Italy and particularly in Tuscany. However, notwithstanding only few laudable exceptions, studies and field measuring campaigns of sand supply to beaches have been very sporadic and limited to a handful of rivers (IDROSER, 1983; Billi & Salemi, 2004; Billi *et al.*, 2007a; 2007b, 2007c; Billi & Salemi, 2008; Preciso *et al.*, 2012).

These studies emphasized a marked reduction in bedload sediment transport and a reduced supply of sand to beaches as a main factor of beach retreat. Such a decline in bedload yield has been associated with the post WWII industrial development, which implied an uncontrolled exploitation of river bed material, a significant land use/vegetation cover change and different river engineering works (mainly dams and weirs).

Though scientists and land management authorities are well aware of the crucial role played by rivers in supplying sand to the coast and hence to maintain its morphological equilibrium, the field measurement of bedload is not easy and requires large financial and human resources.

For these reasons, throughout the last century, many laboratory studies have significantly contributed to develop hydraulic models to predict bedload yield (e.g., Gomez & Church, 1989), but all these equations

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have limited ranges of application and a comparison with field data demonstrated an error of two (or even more) orders of magnitude. The reasons for this disappointing failure are manifold and they are briefly reviewed in this paper. Future laboratory and field investigations will likely improve the performance of predicting models. However, at the moment, the information obtained from field measurements is still the most valuable; furthermore, bedload data are the most reliable for both river and beach management and hydraulic works design. This study is related to bedload field data measured on a few rivers located in Tuscany and Emilia Romagna. The obtained data are reported and analysed to point out the relevance of field measurement in understanding the current beach erosion process and to stress the role of climate and human impact on the reduction of the sand flux to the beaches of these regions.

2. Bedload transport assessment

Bedload is one of the most important parameters in shaping the river channel and the main supply of sandy sediment to beaches. Bedload transport is controlled by the interaction of a number of factors that make its amount very difficult to be quantified. Moreover, bedload is not a linear process and widely varies in space and time. The main factors controlling the sediment yield are specifically listed below:

1. Sediment production on slopes
   - Weathering processes
   - Soil erosion
   - Soil properties
   - Soil delivery ratio
   - Rainfall regime
   - Rainfall intensity
   - Land use
   - Land cover
2. Deposition and sediment storage
   - Deposition on slopes
   - Alluvial fans
   - Alluvial plains
   - Deltas and beaches
   - In-channel bars
   - Streambed fill
3. Sediment supply (i.e. sediment quantity input from upstream)
   - Supply from slopes
   - River bank erosion
   - Streambed scour
   - Tributaries contributions
4. Sediment quality
   - Grain size
   - Sorting
5. Streambed particle arrangement
   - Streambed armouring (Fig. 1)
   - Particle interlocking
   - Hiding factor (Fig. 2)
   - Pebble clusters
   - Bedforms (Fig. 3)
6. Flow hydraulics
   - Flow velocity
   - Discharge
   - Flow duration curve
   - Flood frequency distribution
   - Transport capacity (Fig. 4)
   - Shear stress
   - Stream power

Fig. 1 - Armouring of a gravel-bed river. Subsurface material D_{50} is typically one-two Phi finer than surface sediment.

Fig. 2 - Particle interlocking and hiding factor. Smaller particles are sheltered from flow drag by larger particles.

Most of laboratory flume experiments investigate factor four to six of the previous list; on the contrary only some of them consider sediment supply (in fact only few flumes are equipped with fine sediment recirculation system or a continuous coarse-grained

Fig. 3 - Dune bedforms in a sandy riverbed. Flow is to the right.

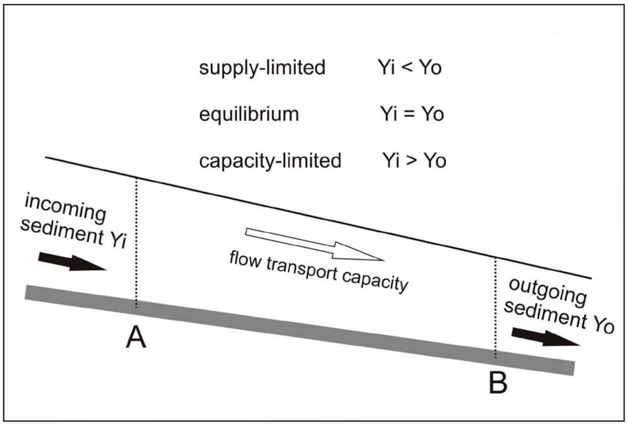
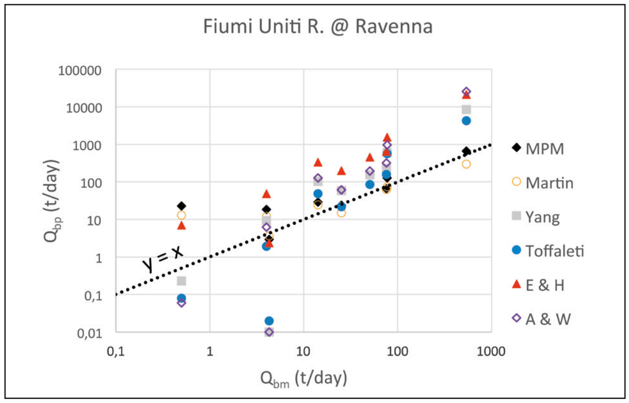
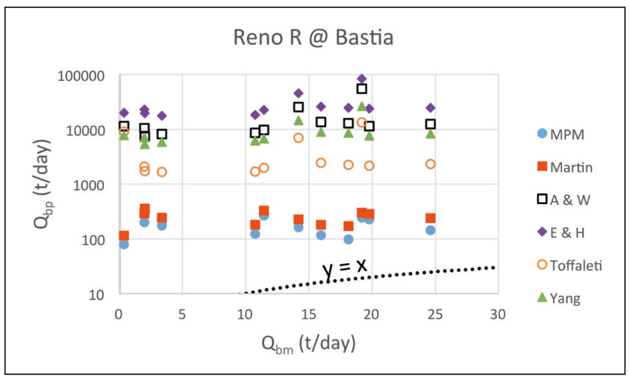


Fig. 4 - Simplified scheme of the relationship between flow energy and sediment supply from upstream. A) upstream cross-section; B) downstream cross-section.



(a)



(b)

Fig. 5 - Plot diagrams of measured versus predicted bedload rates using a few of the most renown equations reported in the literature for the Fiumi Uniti R. (a) and the Reno R. (b). In the Fiumi Uniti R. we have a sustained sediment supply and almost equilibrium conditions. In the Reno R. a sediment supply limited condition is evident.

sediment supply at the upstream side). The reliability of flume studies results is limited also by scale problems such as: the lateral confinement of flow, the lack of natural banks and an inadequate representation of form resistance. For these reasons, though dozens of bedload equations have been developed from laboratory experiments (e.g., Gomez & Church, 1989; Reckling *et al.*, 2012), their applicability is commonly restricted to specific conditions. In fact, they fail to predict bedload rate with a sufficient grade of accuracy when tested against field data (Fig. 5). Since most of bedload equations are expressed as a power function of the excess shear stress, stream power (or discharge) with respect to the critical value of these parameters, another source of uncertainty is the definitions of the critical conditions and their numerical expression. Yet, the role of sand in a sandy gravel mixture and the selection of an appropriate characteristic diameter, representative of the sediment mixture, implies additional elements of uncertainty. All these inaccuracies lead bedload models to under-predict or to over-predict bedload by two-three orders of magnitudes (Fig. 5).

The difficulty to define a reliable framework to quantify bedload stands also in the complexity and the scarcity of field measurements. In fact, though the field measurement of bedload is the best way to quantify the sand flux to beaches, some operational constraints and the need for large financial and human resources have restricted the number and the duration of field measurement campaigns all over the world. In practice, today we can count only on one relatively reliable and internationally accepted instrument to measure bedload, the Helley-Smith sampler (Helley & Smith, 1971) (Fig. 6). A few fixed, very expensive experimental stations provided data of excellent quality but, typically, they are installed on small streams and are representative of specific environmental conditions; hence, their results and models are scarcely exportable to other river systems in different geographical and climatic settings. The most important constraint of the Helley-Smith sampler stands in the maximum particle size of bedload which should not exceed 20 mm. This is a serious limitation of the sampler, preventing its use on gravel bed rivers, whereas it is uninfluential in sand bed streams.

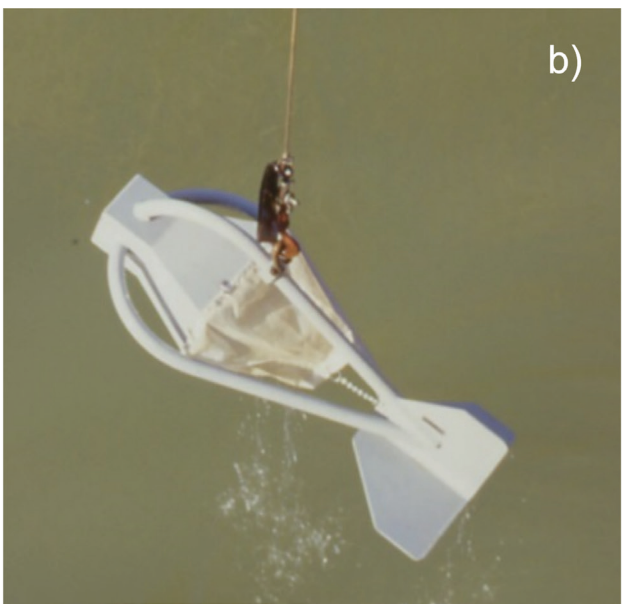


Fig. 6 - The Helley-Smith bedload sampler: a) standard size; b) large size.

Nevertheless, in setting the sampling procedure on a fine grained river some other important issues must be taken into consideration in order to get reliable samples and to interpret the bedload transport rates measured. These factors include the occurrence of migrating dune bedforms (Fig. 3), bedload pulses and seasonal variations and cause the scattering of data around the theoretical flow-bedload rating curve. Finally, a further, more important factor, negatively affecting the accuracy of bedload equations and causing the non-linear relationship between bedload and flow energy, is the sediment supply (Fig. 4). For practical and operational reasons, in fact, most of flume experiments are conducted at flow capacity saturation and, for this reason, the majority of bedload equations tend to over-predict the transport rate. In a natural river, instead, the flow transport capacity ranges from the critical hydraulic conditions (associated with the threshold of bed particle entrainment) to saturation in response to the volume of runoff and sediment supply. It is rather common, in fact, to observe a markedly different bedload transport rate for the same discharge of the rising and the receding limb of the flood hydrograph.

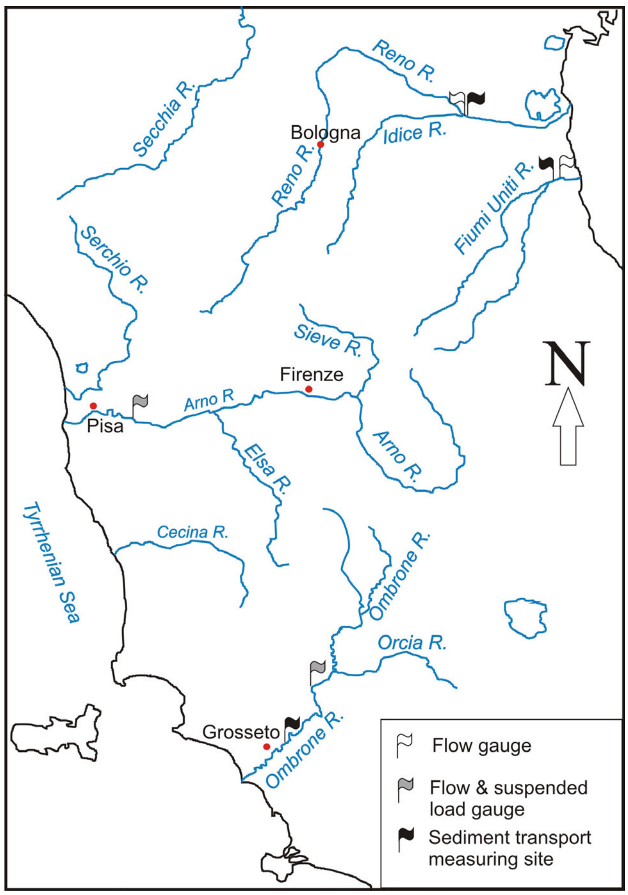


Fig. 7 - Study rivers location map.

Sediment supply may change at both short and long time scales. Bank collapse upstream of the measuring site, the out of phase bedload contribution of larger tributaries, in channel deposition or dams flow routing are the most common causes of short term sediment supply variations, whereas land use/cover change, bed material exploitation, reservoirs and other engineering works have more effect on the long term variations.

Notwithstanding these difficulties, inaccuracies, limitations and variabilities, the Helley-Smith sampler, or other similar samplers of evident derivation from it (such as the Toutle River bedload sampler – Childers, 1999), is today the only instrument that we can rely on to measure bedload in the field. In this study, results of field bedload measurements on some northern Apennines rivers are reported and commented within a global change framework (Fig. 7).

An additional, very promising method that has been used in the Fiumi Uniti R. is the dune migration method.

Extensive research has been conducted on sand dunes as a particular type of alluvial bedforms. Dunes are found mainly on sand-bed rivers, but can form also in gravelly sand bed streams. Best (2005) completed a comprehensive review of dunes and the processes associated to their formation. Numerical works on dune evolution and dune migration are also available (e.g. Carling *et al.*, 2000; Giri & Shimizu, 2006).

Dunes are simply the response of sandy bed material to flow drag. As soon as the sand particles move, the streambed is moulded into bedforms of various shape and size, which migrate downstream. Many studies have investigated the geometry and migration rate of dunes to estimate bed material transport rates (e.g. Van den Berg, 1987; Kostaschuk & Ilersich, 1995; Claude *et al.*, 2012). Assuming a triangular shape of dunes the dune continuity equation is:

$$q_b = (1\text{-}p)U_d H/2 \quad \text{(Yang, 1996)} \qquad [1]$$

in which q_b is unit bedload transport rate ($m^3 s^{-1}$ per unit width); p is porosity (dimensionless); U_d is dune celerity (m day^{-1}) and H is average height of triangular dunes (m).

Eq. [1] has been tested versus the field data of bedload measured on the Fiumi Uniti R. (Fig. 7). The dune geometry has been measured with an echo sounder and the dune migration celerity has been calculated by the equation of Carling *et al.* (2000):

$$U_d = 5.67\ v^{2.04} \qquad [2]$$

where U_d is in m day^{-1} and v is mean flow velocity in m s^{-1}.

The comparison of bedload rate measured and assessed by the dune method is reported in figure 8.

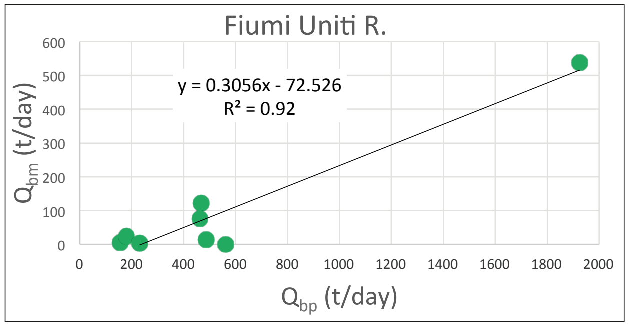


Fig. 8 - Predicted (by the dune method) (Q_{bp}) versus measured (Q_{bm}) bedload rates.

Figure 8 confirms that the dune method is very promising, though further investigation is necessary, especially to define a more accurate criterion for the dune migration celerity calculation under different flow velocity and depth. In this regard, it is crucial also to define a method to compensate the slower dune geometry adaptation rate, which becomes out of phase with the faster rate of flow change during floods.

3. Field measurements

Bedload and suspended sediment transport field measurements have been carried out on the Ombrone River at Istia d'Ombrone (Fig. 7) from 1998 to 2000 (Regione Toscana, 2001). The Helley-Smith sampler (Fig. 6) was used for bedload and the US DH-74 sampler for suspended load.

Grain size characteristics of both bed material and of a composite bedload sample, formed by averaging all the samples collected at the measuring site, are reported in Table 1 and figure 9. These data indicate that the median grain size of bedload is in the field of medium to coarse sand, i.e. about one order of magnitude smaller than bed material D_{50}.

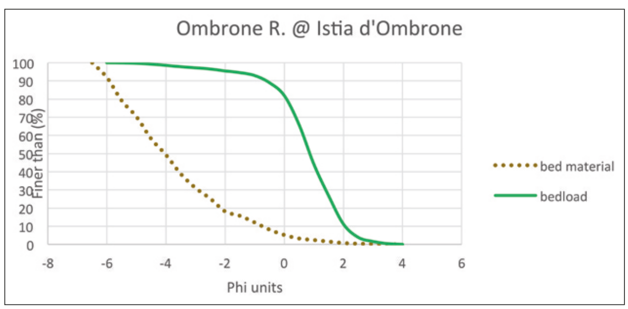


Fig. 9 - Grain-size distribution of bed material and of a composite sample obtained from all the bedload samples collected during the 1998-2000 field measuring campaign on the Ombrone R. at Istia d'Ombrone.

Table 1 - Grain size characteristics of bed material and bedload transport at the Ombrone R. measuring station of Istia d'Ombrone.

	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	s	Gravel (%)	Sand (%)
Bed material	2.95	16.51	51.69	1.97	88	12
Bedload	0.28	0.55	1.11	1.32	7	93

Surprisingly, the field measurements returned a very good correlation between discharge and both bed and suspended load transport (Fig. 10 and 11). By these data and field observations it was possible also to assess the critical discharge for the entrainment of median size bedload particles, which was calculated by the Shields criterion to be around 70 m^3s^{-1}. Then the average discharge exceeding 10 days a year (Q_{10d}) was calculated from the available historical data, recorded at the Sasso d'Ombrone flow gauge across the 1950-2013 interval, and resulted of 130 m^3s^{-1}. The Sasso d'Ombrone recording station is located about 30 km upstream of the bedload measuring site of Istia d'Ombrone, which is about 20 km from the river mouth. Between Sasso and Istia d'Ombrone, a few tributaries, the largest of which are the Melacce and Trasubbie rivers, join the main river. Between Istia and the sea, flow contributions from tributaries are instead negligible.
The Trasubbie and Melacce rivers have a very ephemeral flow regime and their streambed is dry for the largest part of the year. Since these two rivers do not have an appreciable base flow, we can assume that their contribution to Q_{10d} is minimal and, in any case, the discharge of 130 m^3s^{-1} can be assumed as a reference discharge: this value is very close to the critical conditions for substantial movement of a significant volume of bedload.
A comparison between the diagrams represented in figure 10 and 11 shows that the bedload is about 0.2 % of suspended load. This value is very low and provides a first insight into the reasons for the dramatic erosion of the beaches fed by the Ombrone R., which will be discussed later.
According to the interpolation function of figure 10, discharge explains about 99% of the bedload variability. Therefore, we can use this equation to calculate bedload yield for the 1950-2013 interval, using Q_{10d} as the threshold discharge for appreciable quantities of bedload movement. The result is reported in figure 12. It clearly shows a marked decrease of sand supply between the late 1960s and 1980. This period is then followed by a modest sand flux which characterizes the 1988-2008 interval. During this period, in the natural alternation of highs and lows, meagre contributions of sand to the beaches prevail. It is worth noticing that the bedload yield, calculated by the method exposed before, does not take into account the medium to long term variability of catchment sediment supply due, for instance, to land use change or to the replenishment of in channel scours following bed material industrial exploitation.
The mean sand flux, calculated from the data measured at Istia d'Ombrone, is about 2900 t yr^{-1}. However, if we consider that the discharge data used were those measured at Sasso d'Ombrone, from a transformation based on the area/discharge method, we can assume

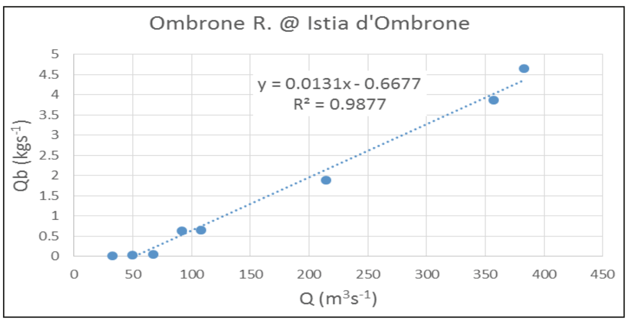


Fig. 10 - Correlation between flow discharge (Q) and bedload transport rate (Qb).

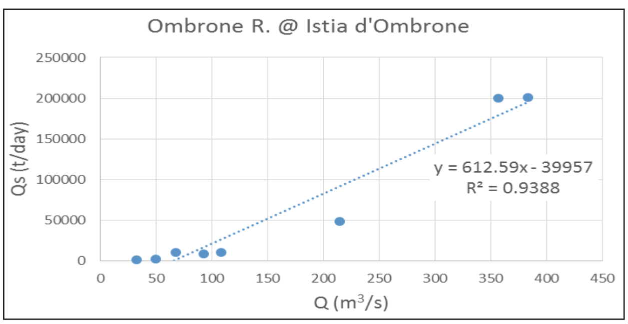


Fig. 11 - Correlation between flow discharge (Q) and suspended sediment transport rate (Qs).

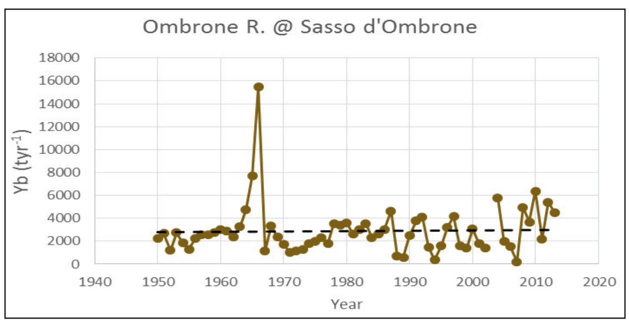


Fig. 12 - Long term variation of bedlaod yield calcualated from historical discharge data measured at the Sasso d'Ombrone flow gauge.

that the real average flux of sand at the Ombrone R. mouth is in the 3100-3400 tyr^{-1} range. Analysis of the suspended sediment data, measured by the National Hydrographic service and after the 1990s by the Tuscany Region Hydrology Department, returns an average suspended load yield of about 1,240,000 tons per year. Yet, the proportion of bedload to suspended load yield is 0.2-03 %, confirming the field data measured at Istia d'Ombrone.

4. Trendlines and long term variability of sediment transport

In the literature, it is well known that the proportion of bedload to suspended load is highly variable and depends on many factors such as climate, vegetation cover, local physiography (mountain streams vs lowland rivers), etc. The data measured at Istia d'Ombrone show a very good correlation between suspended and bedload sediment transport (Fig. 13).
Suspended sediment transport, in fact, explains 95 % of the variability of bedload. Though the proportion of bedload is very small and likely it has changed during the last half century, we can consider the variation through time of the suspended sediment yield data (measured by the national and regional hydrographic services) in order to analyse the changes and trend lines of this parameter as a surrogate of bedload yield during the last 5-7 decades. For this purpose, the suspended yield data of the two largest rivers of Tuscany, i.e. the Arno and the Ombrone, were used (Fig. 7). Unfortunately, in Italy, suspended yield data are very poor and span only a few decades. Moreover, the time series are commonly affected by gaps that cannot be filled with usual procedure because very few rivers are monitored and amongst them very few have a rather long and continuous record. The Arno river data, measured at S.Giovanni alla Vena station, cover an interval of 35 years from 1954 to 1997 (with an important gap around the 1980s-1990s transition, whereas the Ombrone river flow gauge of Sasso d'Ombrone has a longer (38 years) and continuous series, but the suspended sediment yield measurements ceased in 1991. The variation through time of suspended sediment yield (SSY) of these two rivers is reported in figure 14. For both rivers a declining trend is evident, with lower values across the 1970s and the early 1980s. Annual precipitation data of both river catchments for the same time interval are reported in figure 15, which shows a modest decreasing trend with less inter-annual variability compared to SSY.

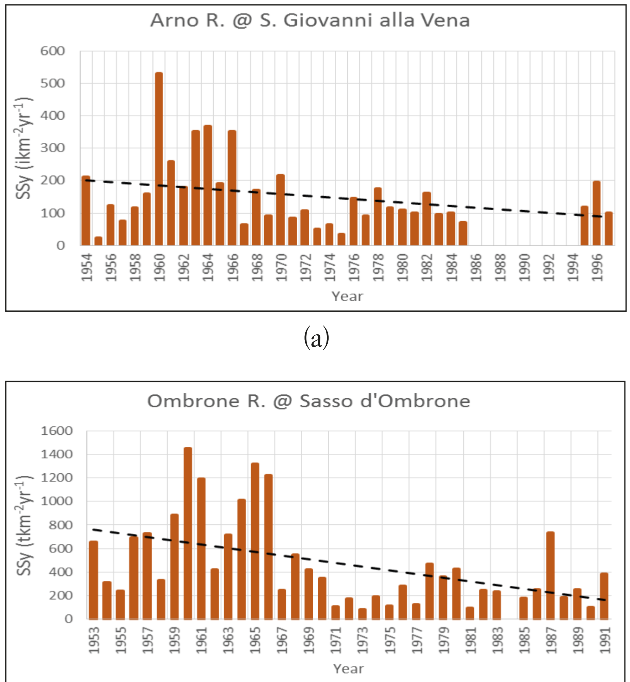


Fig. 14 - Inter-annual variation of suspended sediment yield measured on the Arno (a) and the Ombrone (b) rivers.

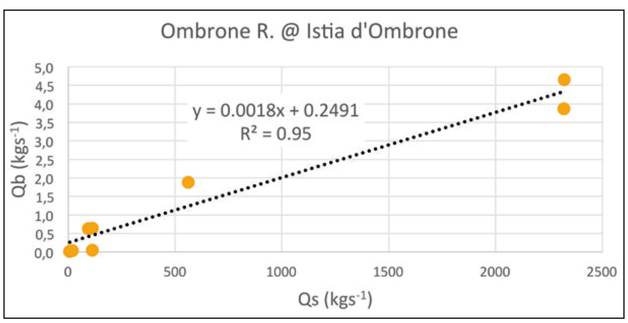
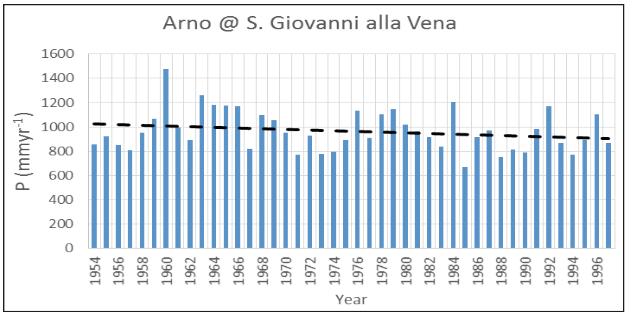
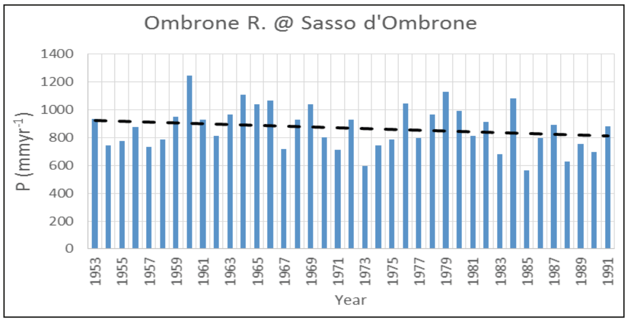


Fig. 13 - Correlation between suspended (Qs) and bedload (Qb) transport rates measured at the study site of Istia d'Ombrone (Fig. 7).

The plot diagrams of annual precipitation (P) versus SSY for both rivers (Fig. 16) confirm a limited role of rainfall in determining the amount of SSY ($R^2 = 0.55$ and 0.48 for Arno and Ombrone, respectively). In the Mediterranean environment, maximum discharge is commonly associated with floods and one should expect that the larger maximum discharge the higher SSY (e.g., De Girolamo *et al.*, 2015). This is not the case of the study rivers as maximum discharge is even less effective than rainfall in accounting for SSY ($R^2 = 0.41$ and 0.33 for Arno and Ombrone, respectively). This result is not surprising and many papers have pointed out the high variability of SSY (Milliman & Syvitski, 1992; Walling & Webb, 1996; Meybeck *et al.*, 2003). However, if we consider the discharge exceeded 10 days a year (Q_{10d}), the correlation with



(a)

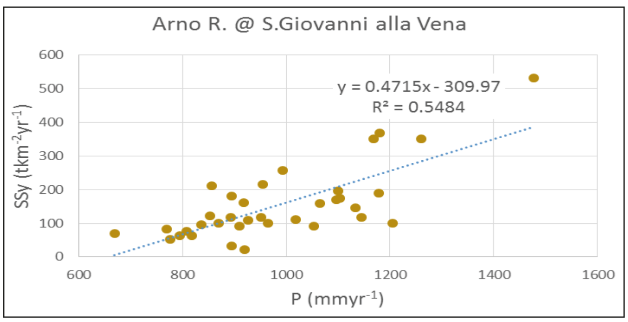


(b)

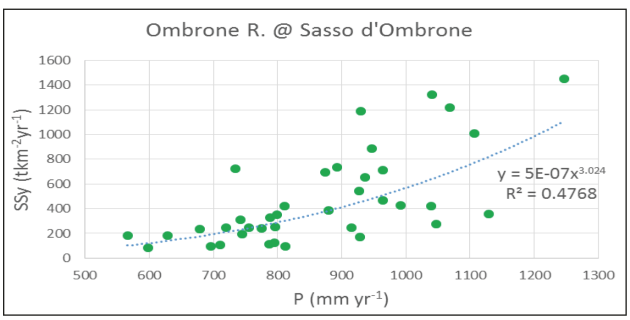
Fig. 15 - Inter-annual variation of precipitation on the two study rivers: a) Arno; b) Ombrone.

SSY improves (though not significantly) (Fig. 17). Moreover, it attests that this characteristic discharge, which is close to the critical condition also for bed material suspension (see previous section), can be taken as a reference flow to investigate the variability of the sediment flux to beaches.

In order to analyze the role of discharge variability in the observed decrease of sediment supply to beaches of Tuscany, the time series of maximum discharge (Q_{max}) and Q_{10d} for both the Arno and Ombrone rivers are reported respectively in figure 18 and 19. These diagrams show a clear decreasing trend for both rivers and discharges. The most worrying indication of figures 18 and 19 is that Q_{10d} tends to depart from long term bankfull discharge. Bankfull discharge is commonly associated with the "dominant discharge", i.e. the flow which performs most work in terms of sediment transport and, in the long term, yields the largest part of the sediment load (Wolman & Miller, 1960). Though there is some uncertainty about which discharge best approximates bankfull discharge, especially for rivers under different climate and flow regime. Many authors (e.g,, Leopold *et al*., 1964; Andrews, 1980; Torizzo & Pitlick, 2004) restrict bankfull flow to a discharge with a return time ranging from 1.58 to 2.33 years. In this study the flow with 1.58 years return time (i.e. the modal flood class, or the most recurrent flood, of the Gumbel extreme values distribution) was used.

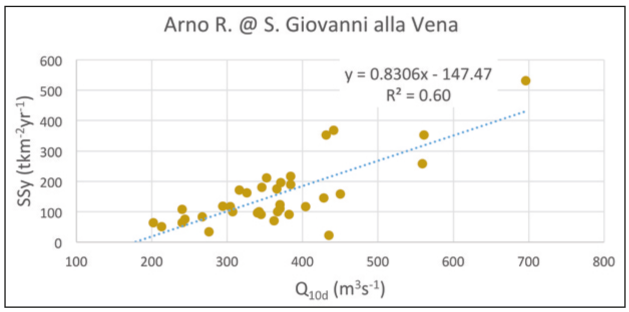


(a)



(b)

Fig. 16 - Correlation between annual precipitation (P) and suspended sediment yield (SSY).



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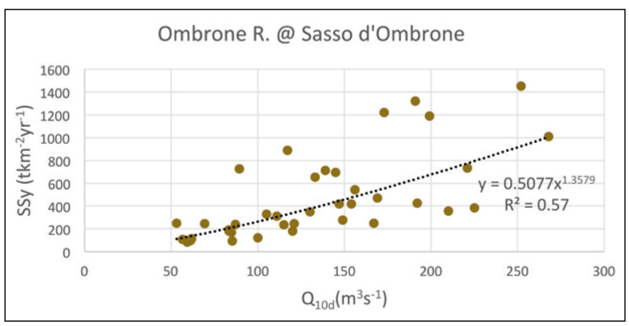

(b)

Fig. 17 - Correlation between the discharge exceeded 10 days a year (Q_{10d}) and suspended sediment yield (SSY).

Since bankfull flow is the discharge which makes the most of work in sediment transport, it is also responsible for the largest supply of sediment to beaches, hence, the lower Q_{10d} the less the amount of sediment (bot suspended and bedload) yielded to the sea, and vice versa.

5. Discussion and conclusions

During the last 4-5 decades many beaches of Tuscany have experienced severe erosion problems. Some cases became dramatic and led to the disappearance of kilometers of sandy shores. Among the many factors for such a degrading situation we cannot neglect the important role of the decrease in sediment supply from rivers. The reasons to account for that are manifold, complex and difficult to identify, monitor and quantify. Nevertheless, some experimental field measurements of sediment transport and basic National and Regional Hydrographic Survey data analyses helped to shed some light on the past and ongoing processes controlling sediment yield.

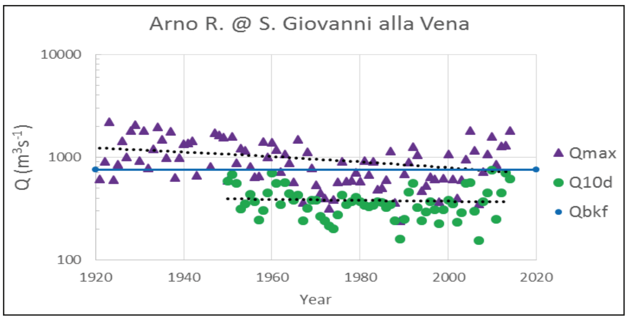

Fig. 18 - Inter-annual variation of annual maximum discharge (Q_{max}) and the discharge exceed 10 days a year (Q_{10d}) for the Arno R. at S. Giovanni alla Vena (i.e. about 35 km upstream of the river mouth). Q_{bkf} is the long term bankfull discharge.

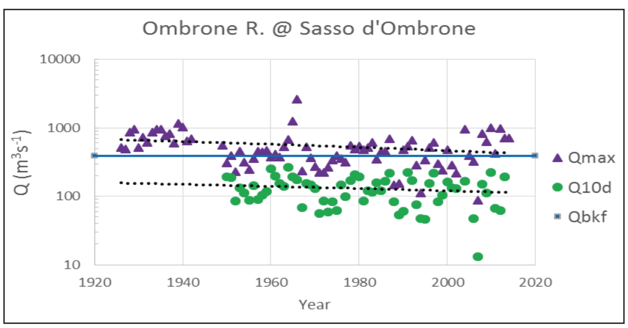

Figure 19 - Inter-annual variation of annual maximum discharge (Qmax) and the discharge exceed 10 days a year (Q_{10d}) for the Ombrone R. at Sasso d'Ombrone (i.e. about 60 km upstream of the river mouth). Q_{bkf} is the long term bankfull discharge.

In a study on land-use/land-cover changes in Italy from 1960 to 2000, Falcucci *et al.* (2007) report an increase in forests, especially in the mountain areas (and in the northern Apennines as well - see their figure 2), an increase in artificial areas (especially in coastal zones), a decrease of pastures, a limited decrease of intensely cultivated areas and a marked decrease of extensively cultivated areas.
All these land use/cover changes contribute significantly to a reduction of sediment production from slopes. In the two main rivers of Tuscany, Arno and Ombrone, considered in this study, precipitation trend lines indicate a moderate decrease during the last decades (Fig. 15), but steeper decreasing trend lines are evident for the discharge exceed 10 days a year (Q_{10d}) and maximum discharge (Q_{max}). This can be interpreted as resulting from the combination of land use/cover change and a decreasing trend of annual precipitation. Forests, in fact, intercepts rainfall and contribute substantially to reduce runoff and flatten flood peaks. The combination of a marked reduction in the quantity of sediment released from slopes with decreasing discharges associated with the more frequent floods, represented by Q_{10d}, can only lead to a reduction in the sand supply to the beaches. In simpler words: less sediment supply and smaller discharges = more beach erosion. Moreover, if we consider that during the 1970s and 1980s huge amounts of sediment have been extracted from the streambed of the study rivers for industrial purposes, the scenario of hungry beaches not sufficiently fed by rivers is completed.
The few sediment transport field measurements, carried out in three rivers of the northern Apennines, namely the Ombrone, Reno and Fiumi Uniti, confirm a more (Reno) or less (Fiumi Uniti) serious sediment supply limited condition for these rivers. This result is even more worrying in a future perspective of beach starvation, given the decreasing trend of discharge associated with the more frequent small to medium floods. Though amongst scientists it is definitely accepted that bankfull discharge (i.e. the flood with 1.58-2.33 years return time interval) is the more important discharge in shaping rivers and supplying sediment to beaches in the long term, smaller floods (such as Q_{10d}), predicted to depart from bankfull discharge, lead to depict an even worrying scenario of degradation for the beaches of Tuscany in the coming years, especially if we consider the decreasing rainfall scenario projected for the Mediterranean by many models (UNEP/UNECE, 2016).
Though the field measurements of sediment transport carried out in three northern Apennines rivers are limited in number, greatly contributed to the understanding of the ongoing situation and revealed a scarcity of sand supply to beaches far beyond any expectation. The proportion of bedload to suspended load, in

fact, resulted very low ranging from 0.01 to 0.02 %, i.e. values one-two orders of magnitude smaller than those commonly reported in the scientific literature and in textbooks for coastal river reaches.

The comparison of field data with predictions of some of the most renown bedload formulas showed that their results are unrealistic and affected by an error of as much as three orders of magnitude.

Promising results were obtained with the dune migration method. This procedure deserves to be investigate in more detail including more comparison with field data on bedload rate, measured in different flow and environmental conditions.

Though bedload transport measurement in the field is complex and requires large human and financial resources, its quantification is crucial and should precede any beach restoration plan.

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