Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). IAHS Publ. no. 210, 1992.

Bed sediment characterization in river engineering problems

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ABSTRACT The great spatial and temporal variability of gravel rivers bed material poses several problems relative to either the sampling procedures or the representativeness of the gathered data.

Aiming to investigate such problems, a field bed-sediment survey campaign has been carried out on 25 sampling sites of two Apenninic gravel-bed rivers. The main units sampled were: bar surface, bar sub-surface, riffle and pool. The geometric and hydraulic characteristics of the studied reaches have been estimated, too. A preliminary analysis of the sediment data and their relation to the stream flow hydraulics is presented. The results seem to indicate that only riffle sediments are significantly correlated to bed load dynamics.

INTRODUCTION

Whenever the grain-size characteristics of a river stretch are required for engineering projects, environmental investigations or river dynamics monitoring, a stream bed survey must be carried out. Commonly, this is not a forthcoming goal since two main problems must be faced: the choice of the sampling methodology and the reliability of the gathered data.

The stream bed is typically made up by several physiographic units showing peculiar morphological and sedimentological features which are variable in time and space. Notwithstanding that several sampling methodologies have been proposed and currently used by scientists (Leopold, 1970; Kellerhals & Bray, 1971; Hey & Thorne, 1983; Church et al., 1987), many problems still remain.

First, the intrinsic reliability of the sampling methods; for instance, the truncation at 8 mm which commonly occurs with the grid sampling (Mosley & Tindale, 1985) or the bias affecting the areal sampling due to loss of fine material (Diplas & Fripp, 1991). Secondly, the sample representativness as far as concerns the physical processes controlling the river-bed dynamics: for instance, which physiographic units of the reach under investigation should be considered whenever bed load must be estimated by the available sediment transport equations?

It is well known that such equations require the knowledge of some characteristic grain size of bed material (Gomez & Church, 1989) but the measured values may be largely affected by the spatial variability of sediment size. The problem is even harder when armouring processes occur.

In order to investigate these problems, a bed-material sampling campaign has been carried out on two different gravel-bed rivers of Southern Tuscany where a total of 25 sampling sites were established. The sampling methodology and a preliminary analysis of the gathered data are presented herein.

DESCRIPTION OF THE STUDY AREA

The studied streams are two typical gravel-bed rivers draining the western margin of the Northern Apennines. The Orcia R. (Fig. 1) is located 40 km south of Siena, has a catchment of about 860 km^2 and, its main channel is 60 km long and its annual precipitation is about 800 mm.

The Cecina R. (Fig. 1) shows features similar to those of the Orcia R.; it is, in fact, 70 km long and has a catchment of 900 km^2 while its mean annual precipitation is about 900 mm. In both streams peak discharge can be larger than base

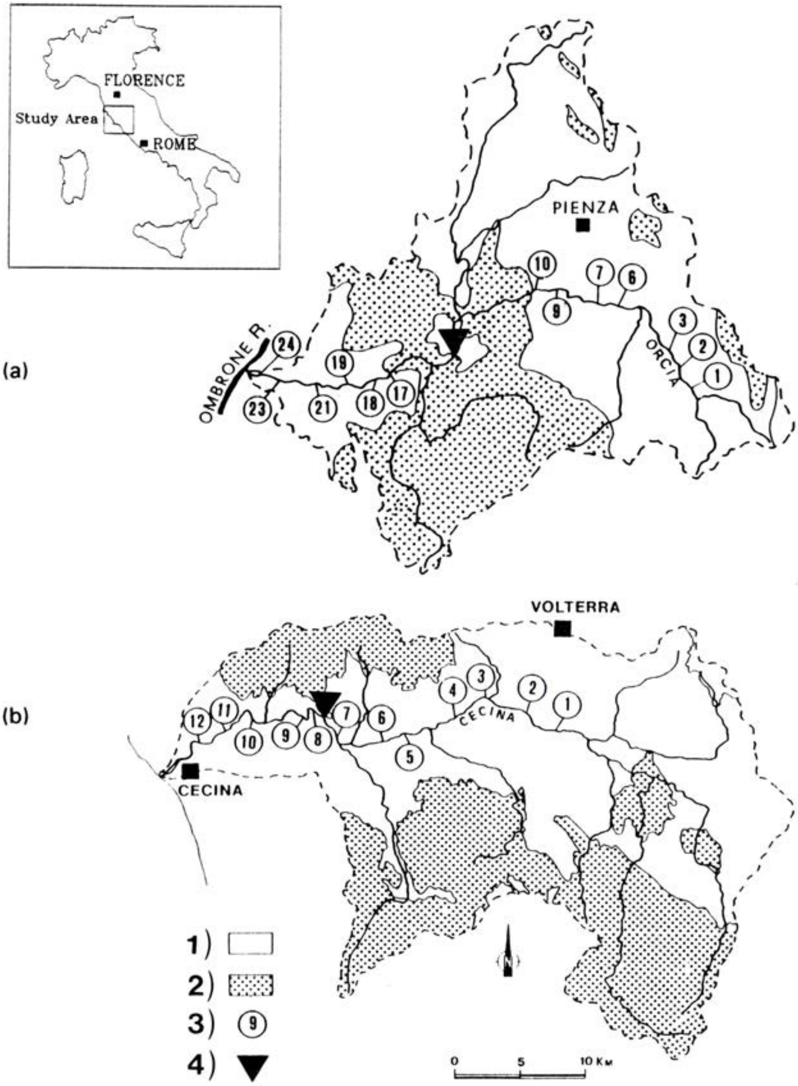

FIG. 1 Sketch map of the Orcia (a) and Cecina (b) rivers. 1) incoherent and semi-coherent rocks; 2) coherent rocks; 3) sampling site; 4) flow gauge.

flow by a factor 1000. This accounts for the flashy character of floods which are sporadic, short and very intense, while, during summer, base flow may be as low as a few hundreds liters per second.

In their upper and middle reaches both streams have a straight channel with alternate lateral bars. The downstream reaches of the Orcia R. have a braided channel morphology which changes into a poorly developed wandering pattern; those of the Cecina R. are instead more sinuous.

PROCEDURES OF DATA COLLECTION

13 and 12 survey sites have been established along the Orcia and the Cecina Rivers respectively (Fig. 1). For each site, bed sediment and channel geometry data were collected by either field measurements or the analysis of 1:10 000 aerial photographic maps, while the hydraulic characteristics have been obtained from the available gauge records (Fig. 1).

Sediment data

The thalweg of gravel-bed rivers commonly consists, at different scale, of many morphological and sedimentary units which have been described in detail by several authors (e.g. Leopold et al., 1964; McGowen & Garner 1970; Bluck, 1971; Bluck, 1979); however, three main larger scale physiographic units can be considered to make up a river bed, they are: bars, riffles and pools. Such units can be considered as suitable sampling locations whose grain-size characteristics reflect the interaction between flow and bed material.

A few authors (Kellerhals & Bray, 1971; Mosley & Tindale, 1985; Church et al., 1987; Billi, 1989; Wolcott & Church, 1991) consider the grid-by-number method (Leopold, 1970) as the most reliable to describe the grain-size distribution of coarse-grained bed material. Unfortunately, the main physiographic units of a gravel river cannot be sampled by only one procedure: for instance, when an armoured layer or practical problems due to the underwater sampling of riffles and pools occur. In the present study, the bar surface has been sampled by the grid method (Leopold, 1970) while bulk samples have been taken from bar sub-surface, riffle and pool.

According to Kellerhals and Bray (1971) grid-by-number samples are equivalent to sieve-by-weight bulk samples, hence the collected samples can be considered homogeneous. This sampling strategy has been adopted in gravel-bed river sediment surveys (e.g. Mosley & Tindale, 1985; Church et al., 1987) notwithstanding a few practical limitations such as the lack of the fine gravel and sandy components occurring with the grid method, as grains smaller than 8 mm are difficult to handle, or the technical problems related to underwater sampling. In an attempt to include also the finer sediment with the grid method a visual grain comparator has been developed and used in the field (Billi, 1990; 1992).

No reliable methods are available for underwater sampling in gravel-bed rivers. In this study riffle and pool bulk samples have been taken by two different procedures. In deep water at least three sub-samples have been collected by a diver using a sort of scoop sampler (Cashman, 1988; Billi, 1989); in shallow water the bed material has been shoveled into an hand operated bucket, having an Helley-Smith sampler bag (Billi, 1992).

Two sub-samples have been collected from the bar subsurface according to the standard procedure which consists in removing the surface layer and collecting a prefixed volume of material underneath (Mosley & Tindale, 1985; Church et al.).

The characteristic diameters of the sampled units are reported in Table 1.

TABLE 1 Sediment characteristics.

Sampling	BAR						RIFFLE			POOL		
site	surface			sub-layer								
	d84 mm	d50 mm	d16 mm	d84 mm	d50 mm	d16 mm	d84 mm	d50 mm	d16 mm	d84 mm	d50 mm	d16 mm
CECINA RIVER												
1	53.8	16.0	0.8	76.1	15.8	1.2	115.4	70.0	36.8	128.0	75.9	28.8
2	64.0	18.9	0.5	119.4	19.2	4.8	107.6	70.3	38.1	73.5	33.7	2.4
3	48.5	16.8	2.5	84.4	23.3	1.8	71.0	45.5	17.8	84.4	45.2	16.0
4	53.8	23.8	9.5	59.7	17.6	1.1	115.4	66.1	46.9	53.8	33.8	4.0
5	46.9	17.6	0.9	42.2	12.2	1.5	53.8	28.8	4.8	6.3	2.8	1.3
6	76.1	17.0	0.6	90.5	31.8	1.0	90.5	66.3	16.0	22.6	10.6	2.2
7	57.7	21.6	5.3	81.6	18.5	1.7	76.1	37.1	11.3	76.1	36.9	1.5
8	53.8	14.5	1.6	52.0	12.6	1.3	35.5	20.2	6.7	26.9	8.3	1.1
9	27.9	8.1	0.4	25.1	19.1	0.8	111.4	80.9	42.2	81.6	55.3	24.3
10	64.0	11.8	0.2	104.0	24.8	0.9	64.0	24.7	6.7	100.4	88.0	45.3
11	32.0	11.0	0.6	42.2	11.7	0.8	35.5	13.4	1.7	45.3	17.0	1.8
12	40.8	13.9	0.5	27.9	9.9	1.3	55.7	26.2	7.5	93.7	48.4	12.6
ORCIA RIVER												
1	107.6	37.0	6.3	152.2	20.2	1.7	152.2	97.7	53.8	16.0	4.6	0.8
2	97.0	40.0	0.9	157.6	81.0	8.0	111.4	69.5	25.1	42.2	19.3	2.8
3	81.6	18.1	0.6	200.9	86.8	18.4	111.4	91.8	59.7	152.2	106.1	53.8
6	81.6	27.5	6.5	163.1	97.7	13.9	115.4	88.6	42.2	100.4	68.1	28.8
7	90.5	22.4	0.2	84.4	37.8	1.3	73.5	29.9	18.4	59.7	35.0	16.6
9	53.8	13.7	0.1	163.1	121.9	6.3	115.4	83.9	38.1	107.6	65.3	27.9
10	61.8	10.7	0.6	163.1	136.2	9.8	84.4	48.5	19.0	53.8	31.3	16.0
17	215.3	89.4	11.3	104.0	45.9	1.2	119.4	92.4	64.0	152.2	88.0	26.9
18	137.2	47.0	10.9	168.9	102.5	3.1	119.4	92.4	53.8	147.0	85.0	36.8
19	142.0	30.4	1.3	81.6	37.3	1.3	53.8	24.6	7.2	152.2	83.3	38.1
21	174.9	71.7	16.0	107.6	36.0	4.8	147.0	101.8	68.6	142.0	98.4	39.4
23	87.4	29.0	3.5	90.5	40.2	13.5	152.2	112.2	90.5	107.6	75.1	36.8
24	111.4	29.5	2.0	157.6	89.3	39.4	152.2	103.2	53.8	128.0	74.0	36.8

Hydraulic data

In order to characterize the hydraulic regime of the river reaches under investigation, the following variables have been considered: bed slope, S, obtained by 1:10,000 topographic maps, bankfull height, h, and width, W, measured in the field during the campaign; daily discharges at 10, 182, and 355 days of exceedance, here indicated as Q_{10}, Q_{182}, Q_{355} respectively, were available from the records of the two gauging stations (Servizio Idrografico, 1980) (fig. 1).

However, morphological and transport phenomena in gravel rivers are generally related to discharges with higher return period. Therefore, a duration curve has been estimated for each gauging station by using a frequency distribution law as proposed by Gibrat, where the reduced variable, z:

$$z = a \cdot \log (Q - Qo) + b \qquad (1)$$

is distributed according a gaussian law.

In eq. 1, Q is the daily discharge and the three parameters, a, Qo and b can be obtained by the known values of Q10, Q182, Q355. Thus, any daily discharge associated to a prefixed duration can be calculated. In the present study the biennial discharge, Qbi, has been assumed as a representative discharge. The calculations of Qbi for the ungauged reaches have been carried out by scaling up the observed discharges according to the catchment areas, A. Results are summarized in Table 2, together with the other hydraulic characteristics.

TABLE 2 Hydraulic characteristics.

Sampling site	A Km^2	Qbi m^{3}s^{-1}	S *1000	h m	W m
CECINA RIVER					
1	397.50	286.00	3.00	2.00	50.00
2	430.00	309.37	5.70	1.00	70.00
3	463.00	333.09	1.60	2.00	80.00
4	495.00	356.10	2.60	1.50	80.00
5	620.00	445.96	1.50	2.50	60.00
6	630.00	453.14	1.80	2.50	60.00
7	795.00	571.73	0.80	3.00	65.00
8	805.00	578.92	3.20	2.50	50.00
9	825.00	593.29	2.10	3.50	60.00
10	845.00	607.67	0.80	4.00	65.00
11	865.00	622.04	4.20	3.00	30.00
12	885.00	636.41	0.80	4.50	40.00
ORCIA RIVER					
1	65.10	29.07	3.23	1.00	60.00
2	76.50	34.16	9.20	1.50	70.00
3	92.10	41.12	6.67	1.00	80.00
6	173.20	77.30	4.55	1.00	90.00
7	212.70	94.91	3.45	1.50	70.00
9	264.90	118.19	4.55	1.50	70.00
10	318.00	141.86	3.16	2.00	70.00
17	739.40	331.36	5.56	2.00	45.00

ANALYSIS OF DATA AND RESULTS

The variability of sediment size along a river bed is generally time and space dependent; natural constrains, such as geological and hydrological characteristics of the catchment, act as boundary conditions of the fluvial system.

Stream flow selectivity and abrasion are two processes which generally control the downstream variation in sediment size. Other than the longitudinal variability, also a transversal and a vertical variability of sediment occur as a result of the lateral variation in sediment transport rate, the erosion and deposition phases, and the armouring processes. From these considerations it is clear that the problem of explaining the variability of bed sediment is extremely complex, at least from a quantitative point of view. It requires a large amount (in space and time) of accurate data together with the availability of adequate schemes to describe all the dominant processes of the river dynamics. Notwithstanding the numerous contributions of the last decades, many aspects of sediment transport phenomena have to be cleared (i.e. cross channel geometry, bar development, armouring processes, riffle and pool sequences).

Nevertheless, some criterion to characterize bed sediment can be useful in engineering problems such as sediment transport evaluations, mathematical and physical model of movable beds. In an attempt to identify the interaction between bed and stream flow characteristics, D84, D50 and D16 have been assumed as significant diameters of each grain-size population.

The hydraulic characteristics of each reach are assumed to be described by:

Qbi = discharge with a 2 years return period, obtained by gauge station records as previously described; Qbi represents the discharge imposed by the upstream catchment portion;

Qbf = bankfull discharge calculated from the measured values of height, width and slope according to the uniform flow equation:

$$Qf = h \cdot W \cdot 7.66 \cdot (h/\epsilon)^{1/6} \cdot \sqrt{ghS} \qquad (2)$$

where ϵ is the roughness height here assumed equal to D84 of riffle grain size distribution and g is the acceleration of gravity. Qbf represents the reach discharge capacity at each sediment sampling site.

Qcr = critical discharge for the entrainment of sediment of size Di estimated by the Schoklitsch formula (in m^3s^{-1}) (1950):

$$Qcr = 0.06 \cdot W \cdot Di^{1.5}/S^{7/6} \qquad (3)$$

According to the original formulation, Di was posed equal to D40. A recent analysis (Bathurst et al.,1987) has shown that D16 is a more appropriate value for Di.

Analysis of data has been carried out assuming the following hypotheses:

- samples are spatially representative of the physiographic units from which they have been collected;
- the hydraulic and geometric characteristics are adequately defined by the available data.

Supposing that the sediment deposited on riffles corresponds to the material moving as bedload during floods, this physiographic unit is assumed as the one whose grain size distribution is more related to the local hydraulic characteristics. Bars are locally subjected to hydraulic conditions, and, consequently, to primary sediment transport phenomena, different from those of the main channel. Furthermore, minor sediment transport processes occur on bars (deposition of very fine material favoured by vegetation, small scale bar dissection), while pools commonly act as finer material traps during the receding flow.

For a preliminary investigation the biennial discharge is plotted versus the bankfull discharge using the critical discharge as a scaling factor, calculated

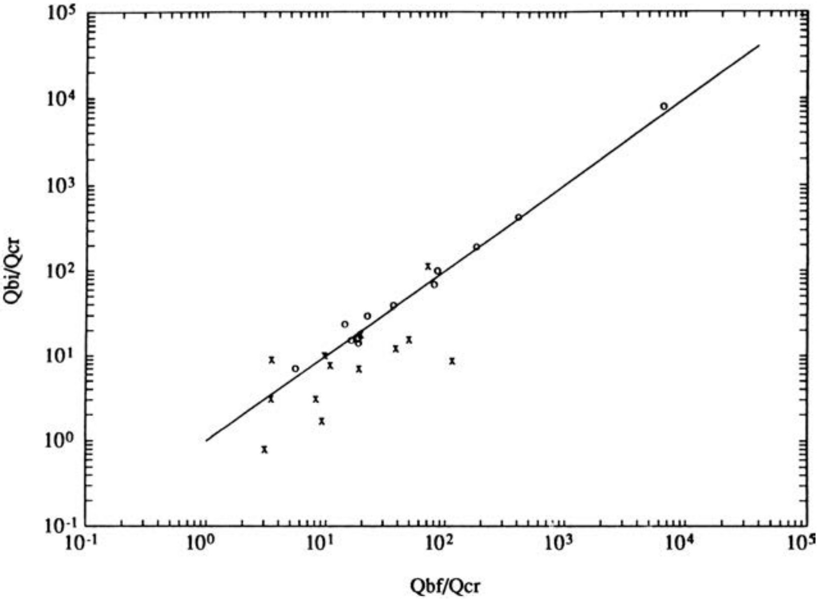

FIG. 2 Biennial discharge vs. bankfull discharge using Qcr as a scaling factor; o: Cecina R., x: Orcia R.

according to eq.3 (Fig. 2). Most of data are well correlated; this implies that the local hydraulic characteristics, calculated for each site, can be assumed to be more or less in equilibrium with the discharge imposed by the upstream catchment and estimated by the method previously described. The scattered values are probably affected by local conditions which are not represented in this scheme (e.g. geological constrains and/or human effects).

Therefore, the biennial discharge is assumed to be representative of the hydraulic regime and the Qbi/Qcr ratio as an index of the bed material mobility.

A further analysis has been carried out in order to characterize the sediment of the different physiographic units through the relations, if any, among the main parameters of their grain-size distributions. The only significant result has been obtained in terms of D84 and D16 of the riffle sediment; in figure 3, it can be seen that D84 and D16 vary accordingly but D16 decreases about 2.5 times faster than D84.

Aiming to verify the assumption that riffle behaviour is more directly controlled by the main sediment transport and sorting processes than pools and bars, its sediment characteristics are related to the dimensionless parameter Qbi/Qcr. In figure 4 the sorting index D84/D16 is plotted against Qbi/Qcr. Notwithstanding some scatter, a significant correlation can be observed again for riffle data only: D84/D16 ratio increases as bed material mobility increases. By contrast, for low mobility values it seems that D84/D16 tends to be approximately constant. It is worth noting that the lower mobility values are associated to coarser sediment surveyed in the uppermost riffles, while a higher mobility is typical of the finer sediment of the downstream ones.

These results indicate that where the discharge imposed by the basin (biennial discharge, Qbi) is close to the critical conditions for particle entrainment (low mobility) the riffle sediment tends to be coarser and better sorted, while as Qbi

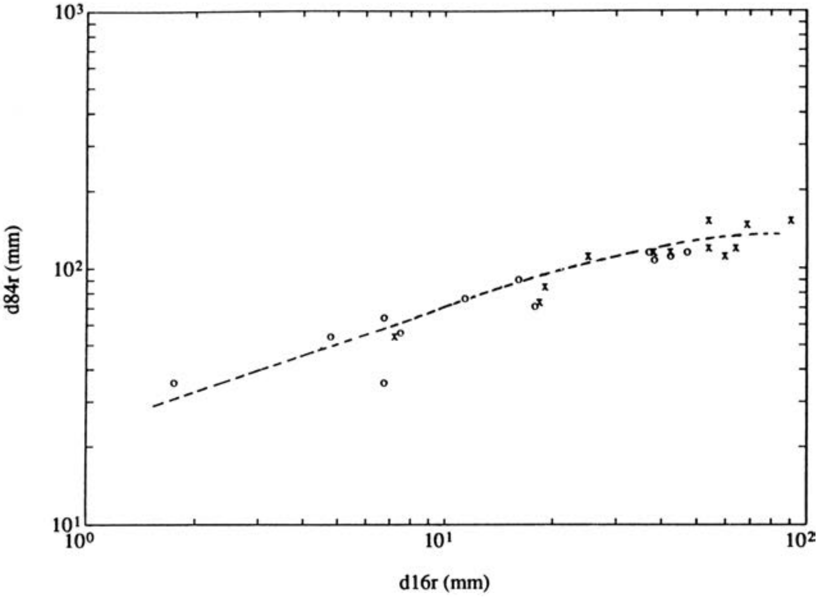

FIG. 3 D84 vs. D16 of riffle sediment; o: Cecina R.; x: Orcia R.

becomes remarkably higher than the critical discharge (high mobility) a coarse fraction is still present, though a certain reduction occurs (Fig. 3), but the increase of the finer fraction is such that sediment becomes poorly sorted.

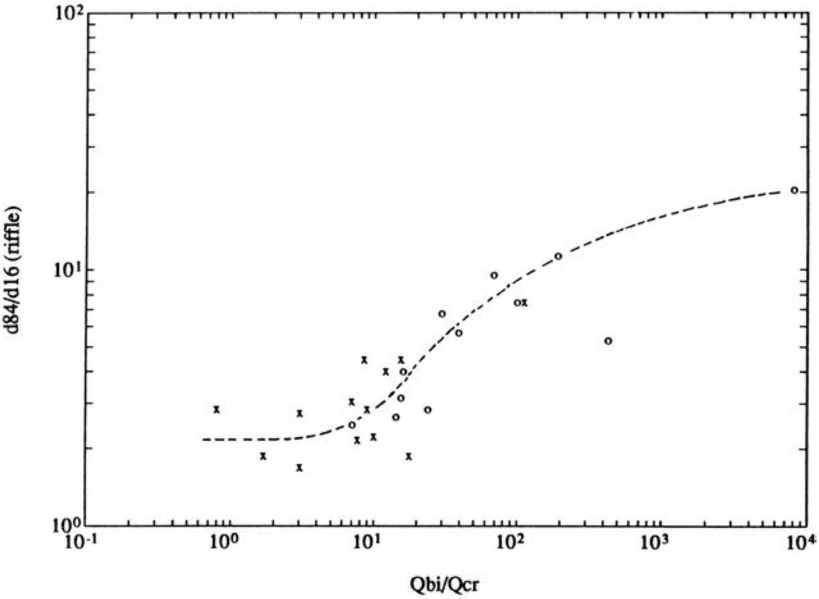

FIG. 4 Riffle sorting index (D84/D16) vs. Qbi/Qcr; o: Cecina R.; x: Orcia R.

CONCLUSIONS

A field sediment survey has been carried out in 25 sampling sites of two gravel rivers of southern Tuscany (Italy) in order to characterize the bed material of the main physiographic units.

At each site the bar surface, bar sub-surface, riffle and pool sediment has been sampled and the grain-size distribution obtained have been analysed in order to investigate the behaviour of each unit with respect to the main fluvial processes. For this purpose, also the hydraulic and geometric characteristics of the studied reaches have been considered. The gathered data are summarized in Table 1 and 2.

The data analysis leads to the following conclusions:

- no relation has been found among the grain-size characteristics of the sampled units;
- within each units the only significant correlation does exist between D84 and D16 of the riffle sediment; in particular it appears that large variations of D16 correspond to relatively small variations of D84 (Fig. 3);
- among the sampled units, the riffle seem to show the best relation with the hydraulic characteristics expressed in terms of biennial and critical discharges. When the biennial discharge is close to the critical value the flow tend to have a more selective capacity giving rise to well sorted riffle sediment; as the flow increases it is capable to entrain more grain-size classes and, therefore, poorly sorted sediment is deposited on riffles.

From these findings it seems reasonably to conclude that the sedimentary population of riffles reflects better than others the bedload transport dynamics of gravel-bed rivers; for this reason is probably more tightly connected to hydraulic characteristic of the stream flow. Consequently, whenever bed load transport processes have to be investigated a monitoring of the riffle sediment is advised.

ACKNOWLEDGEMENTS This paper was financially supported by Ministero della Protezione Civile, Gruppo Grandi Catastrofi and MURST 60%, 1991, University of Udine.

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