Variability of gravel movement on the Virginio gravel-bed stream (central Italy) during some floods

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Abstract A continuous-operation bed load measuring station was installed on the Virginio gravel-bed stream (central Italy), which has a median grain size of about 16 mm (−5 phi) and a straight channel with alternate bars. The slope of the stream at this point is about 0.008 and the basin has an area of 40 km^2. The introduction of a marked sample of about 4000 pebbles upstream from the measuring station made it possible to study the relationships between bed load transport and the passage of pebbles through the reach above the station. It was possible after each flood to measure the position of the pebbles remaining on the surface of the river bed. The results of this study confirm the pulsating nature of bed load transport and its poor correlation with grain-size distribution and water discharge. For each grain-size class, the distance travelled by the pebbles, and their embedding were measured.

INTRODUCTION

The processes of pebble transport in gravel-bed rivers are little known, as is the transport rate. Measurement is very difficult and, apart from small amounts of data gathered in experimental drainage basins and in laboratory flumes, it has been almost impossible to assess either processes on a large scale with great enough accuracy using present-day methods (Emmett, 1981; Tacconi, 1982).

A vortex-tube bed load trap (phi > -1) was installed on Virginio Creek, in the Arno basin, near Baccaiano in Tuscany (Fig. 1). The drainage basin has an area of 40 km^2 and is underlain by Pliocene marine sediments composed of silts, sands and conglomerates. The area is used for cultivating grain, vines and olive trees. It has a Mediterranean climate with an average annual precipitation of 900 mm (Tacconi & Billi, 1987).

The river bed upstream from the measuring station is straight with alternate bars. The banks are thickly vegetated. The average channel width is 12 m and the channel gradient is 0.008.

Fig. 1 Location of study area.

OBSERVATIONS AND MEASUREMENTS

The 1988 experiments consisted of the introduction of a marked sample into a section 250 m upstream from the measuring station and the subsequent analysis of the distances travelled by all visible clasts (not those buried in the river bed) in each grain-size class after the four flood events. For operational reasons, not all the measurements of sediment transport could be continued throughout the entire duration of the observation period.

The marked sample was prepared and called "YELLOW". It ranged in size between -4 and -7 phi and was composed of 3935 pebbles weighting a total of 337 kg. Besides this "YELLOW", a "RED" sample was introduced composed of 300 pebbles with sizes between -4.5 and -5.5 phi and representative of the three forms in Folk's shape classification (spherical, discoidal, elongate). The pebbles were taken from Virginio Creek in order to ensure identical lithological features (limestones) to those normally found in the river bed. The clasts of the "RED" sample were numbered, enabling close study of their movements.

Table 1 shows the grain-size data of the samples of the river bed and of the marked sample.

OBSERVED FLOOD EVENTS

Flood no. 1 (14 April 1988)

This was a small event with a maximum discharge of about 3 $m^3\ s^{-1}$ and a duration of 24 h. The sediment discharge was not measured.

Table 1 Grain-size features of sediments in the river bed and the marked sample.

		Bars: Armour	Subarmour	Channel armour	YELLOW sample
Mean diameter (phi)		−5.96	−4.93	−6.38	−6.03
Standard deviation (phi)		0.687	1.287	0.634	0.77
Skewness		0.558	1.394	0.679	0.87
Kurtosis		3.413	5.187	3.150	2.64
D10 (phi)		−5.05	−3.28	−5.51	−4.74
D50 (phi)		−6.03	−5.18	−6.48	−6.24
D90 (phi)		−6.83	−6.28	−7.18	−6.87
Grain-size classes		Number of clasts	Weight (kg)	Mean weight of clasts (g)	Morphometry
YELLOW sample					
−4.0	−4.5	2000	20	10	
−4.5	−5.0	1000	28	28	
−5.0	−5.5	500	32	64	
−5.5	−6.0	250	50	200	
−6.0	−6.5	125	80	640	
−6.5	−7.0	60	127	2117	
−4.0	−7.0	3935	337	85.6	
RED sample					
−4.5	−5.5	300	8.5	28.3	n. 100 elongate n. 100 discoidal n. 100 spherical

Flood no. 2 (20 May 1988)

This was the largest flood of the four observed and was associated with four precipitation events. A first peak of about 4 $m^3 s^{-1}$ was registered followed by the mean peak with a discharge of 17 $m^3 s^{-1}$. The record of sediment discharge is not complete; in fact, by the time that the measuring station was made operational, some marked pebbles were found to have entered the vortex-tube and these must have travelled along a section of the order of 250 m. Unfortunately, 30 minutes after the start of the recordings, and due to operational problems connected with the high rate of bed load transport, measuring was stopped for 50 minutes. A maximum bed load transport of 580 kg min^{-1} was recorded, and 2110 kg in 5 minutes was recorded. This is the highest level of sediment discharge ever recorded at the measuring station since its installation in 1983. The total sediment discharge of this flood was about 43 260 kg. Although

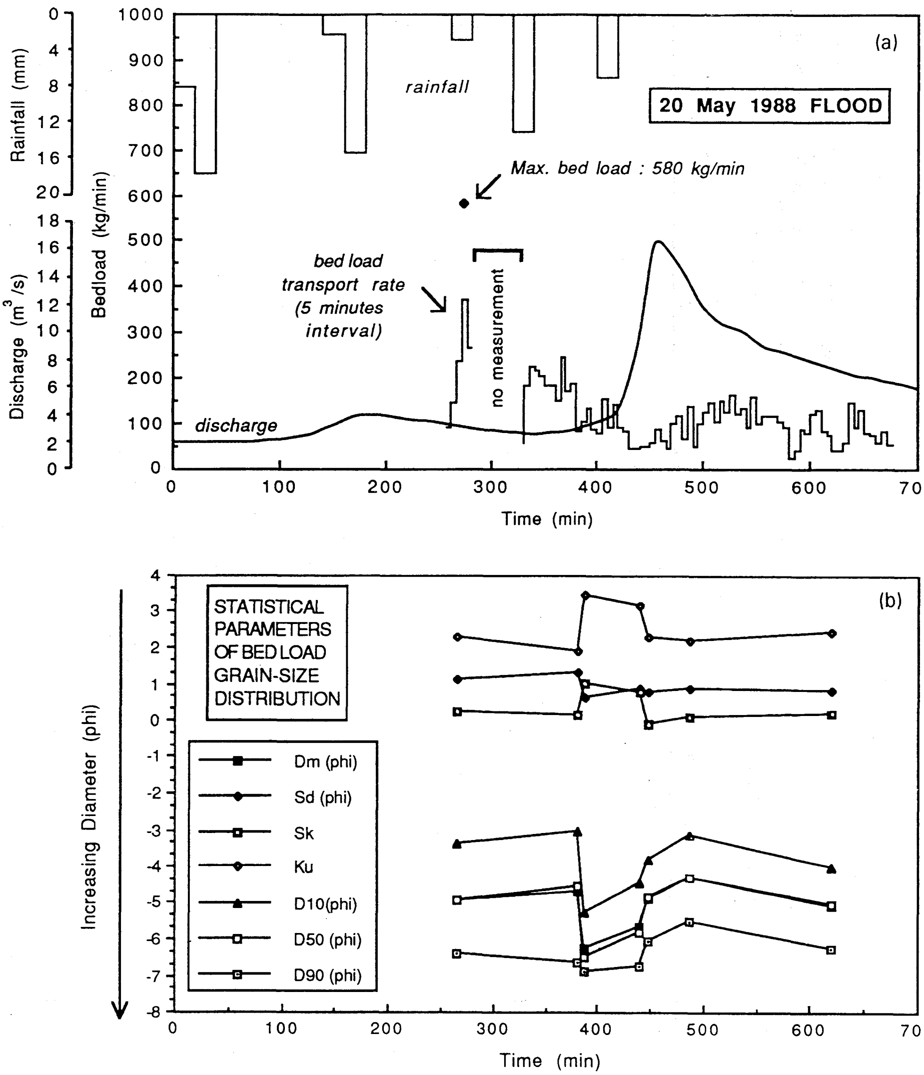
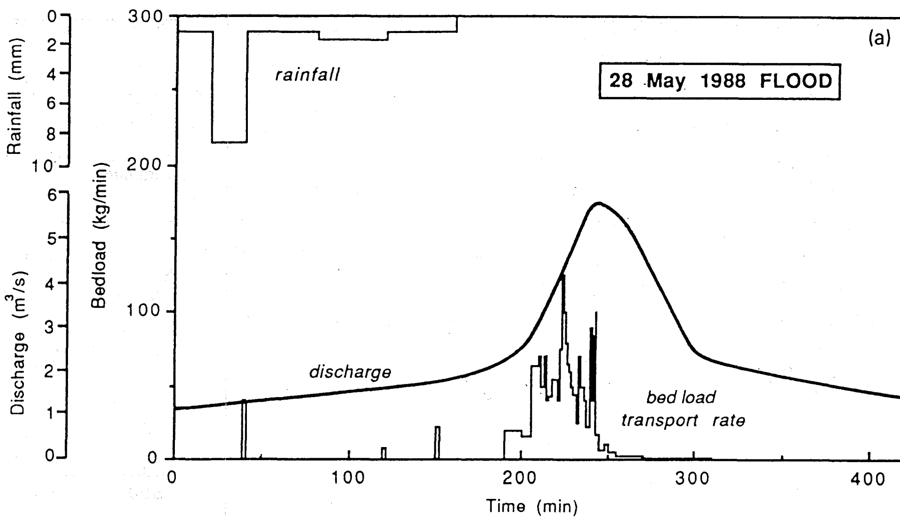


Fig. 2 20 May 1988 flood: (a) rainfall, discharge and bed load; (b) statistical parameters range for the bed load samples. *Dm*: mean diameter; *Sd*: standard deviation; *Sk*: skewness; *Ku*: kurtosis; *D10*, *D50*, *D90*: diameters for 10, 50, 90 percentiles.

interrupted, measuring continued for more than 48 h, during which further data was not gathered. The recorded data are shown in greater detail in Fig. 2.

Flood no. 3 (28 May 1988)

Despite being smaller, the third flood carried all clast sizes. The length of the flood wave was 7 h, with a peak discharge of 6 m^3 s^{-1}. The maximum sediment discharge measured was 125 kg min^{-1} while the total sediment discharge was 2780 kg. A few isolated arrivals of bed load preceded a real state of continuous motion. The initial



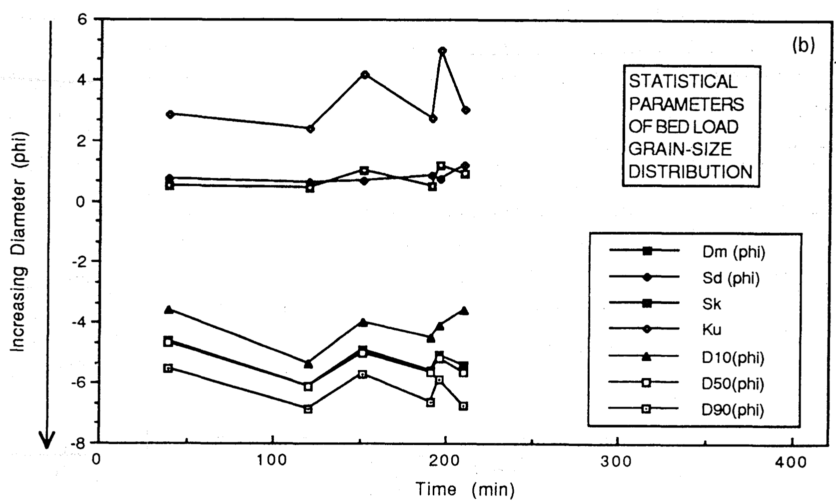


Fig. 3 28 May 1988 flood: (a) rainfall, discharge and bed load; (b) statistical parameters range for the bed load samples. *Dm*: mean diameter; *Sd*: standard deviation; *Sk*: skewness; *Ku*: kurtosis; *D10*, *D50*, *D90*: diameters for 10, 50, 90 percentiles.

condition of sediment movement was easily recognizable, and at a water discharge of little more than 2 $m^3 s^{-1}$ (Fig. 3). The sediment supply was exhausted quickly in this event soon after the peak discharge.

Flood no. 4 (5 June 1988)

This event lasted a considerable amount of time and had a peak discharge of 4.9 $m^3 s^{-1}$. Although instantaneous data for sediment discharge are not available, it was observed that, at the end of the event, the vortex-tube contained 450 kg of material instead of its maximum capacity of 700 kg. This result may be taken as a measure of total bed load transport. This material was composed of fine sediments and of mud balls with a few pebbles of medium size. It may be concluded that the event was characterized by high concentration of suspended sediment linked to pronounced bank and slope erosion, and to the supply from the tributaries situated upstream to the measuring station. The small amount of bed load may be explained by a higher degree of armouring of the river bed. However, the hydrograph does not display abrupt variations in discharge even during the rising stage and this may also account for low bed load discharge. Moreover it could be a bed load from lateral sedimentary supply, which was then deposited and remained stable on the armour. This is supported by means of the marked pebbles analysis. In fact the number of marked pebbles after flood no. 4 is much less than before; this may be due to the pebbles burying previously transported ones.

MOVEMENT OF THE MARKED PEBBLES

The clasts that were visible after each flood were examined in order to determine their dimensions and the distance they had travelled.

During periods in which bed load transport rates were being measured, any marked clasts arriving in the vortex-tube were recorded and thrown immediately back into the flow downstream from the measuring station; during periods in which the measuring station was not in operation all clasts, except those filling the vortex-tube passed freely downstream from the measuring station. This enabled us to follow the "cloud" of clasts even in the section downstream from the measuring station. The position of the clasts related to each flood event is shown in Fig. 4 while Fig. 5 shows the distance range of the marked pebbles for each grain-size class.

Flood no. 1 brought about only a slight redistribution of the marked sample, with a maximum travel distance recorded of 18 m. Bed load discharge was not determined

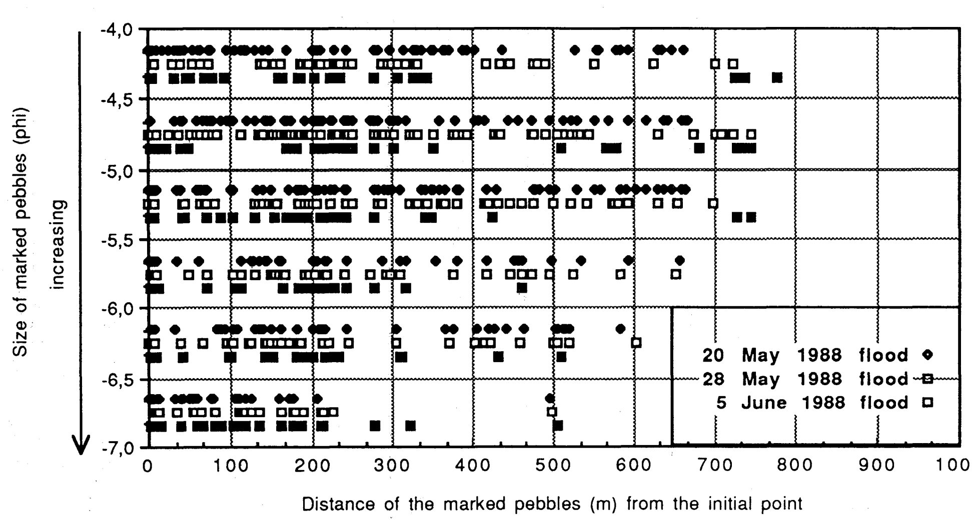


Fig. 4 Distribution of marked pebbles after the floods as a function of their relative size.

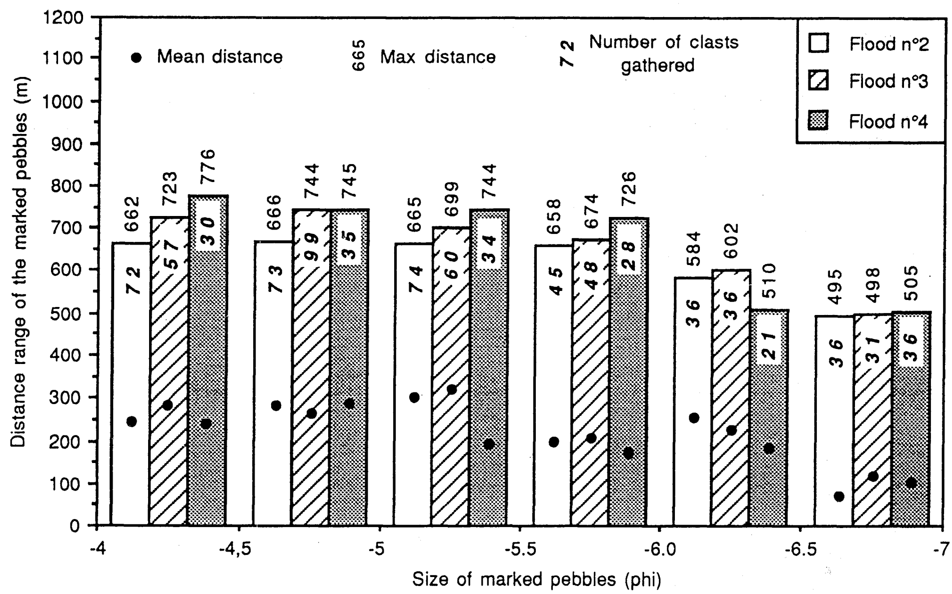


Fig. 5 Distance range of marked pebbles (m) as a function of their relative size.

and this flood was used to move the marked sample into positions that would be closer to a natural condition.

Flood no. 2 caused the greatest movement of marked pebbles as a corollary of the greater sediment discharge; the marked clasts were discovered on the surface up to 666 m away from the introduction point (i.e. they had moved through the bed load trap).

Following floods no. 3 and no. 4, the maximum distances travelled by marked pebbles were 744 m and 776 m respectively. The centroid of the pebble cloud was 235 m from the introduction point after the second flood; 246 m after the third flood and 192 m after the fourth flood.

The river bed survey continued for another 1000 m downstream from the last pebble found in the river bed; consequently, that part of the sample that was not found must have been buried in the bed of the channel.

OBSERVATIONS AND DISCUSSION

Observations of bed load

The two events for which bed load discharge measurements are available, confirm its extreme temporal variability and its pulse-like nature (Tacconi & Billi, 1987).

During flood no. 3, a few short bursts of bed load may be noted which greatly precede the general wave of mobile sediment. These early arrivals could be a result of either partial lateral erosion of bars and/or banks, or contributions from tributaries, or the movement of clasts deposited on top of the armour during the terminal stage of the preceding flood (20 May 1988).

Observations of the YELLOW sample

There are many observations to be made here, yet it should remembered that during flood no. 4 there was an anomalous deposition of sediments and very low bed load transport rates.

Number of rediscovered pebbles

The first observation concerns the number of pebbles rediscovered in the river bed after floods (Fig. 6). This amounts to 8.6% of the total after flood no. 2; 8.4% of the total after flood no. 3 and 4.7% of the total after flood no. 4. This last percentage may be explained by deposition of sediments as described earlier. This means that 91.2% of the

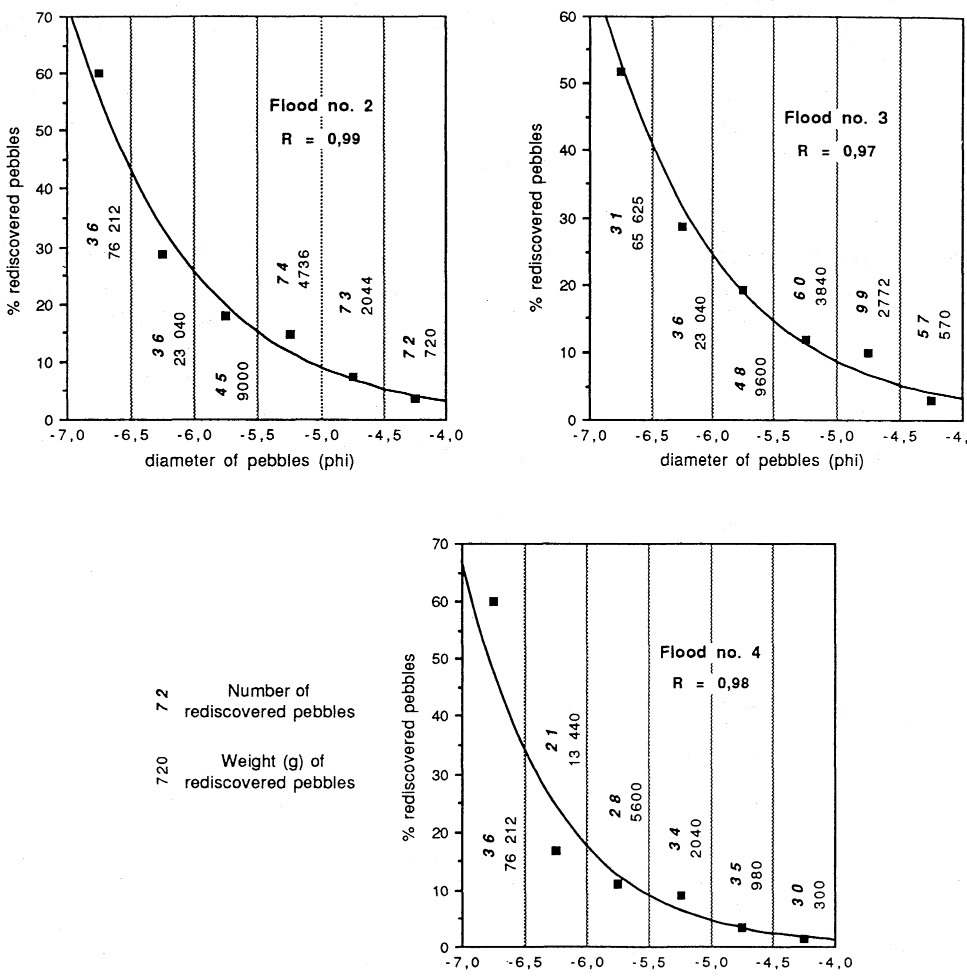


Fig. 6 Relationships between size of marked pebbles (phi) and percentage of pebbles rediscovered in relation to the marked sample (%) for each grain-size class.

pebbles remained buried after flood no. 2; 91.6% after flood no. 3 and 95.3% after flood no. 4. This rate of burial is very high.

If we look at this phenomenon in relation to each grain-size class, we see how this rate is very high for the small grain-sizes and diminishes exponentially with an increase in clast size (Fig. 6). The percentage of the clasts rediscovered after flood no. 2 in terms of weight is 34.3% (115 752 g); after flood no. 3 it is 31.3% (105 449 g) and after flood no. 4 it is 29.2% (98 572 g).

Shifting of marked pebbles

A synthetic view of the clasts' movements of the YELLOW sample is shown in Figs 4 and 5, where the statistical parameters of the movements of marked pebbles, subdivided into grain-size classes, are displayed.

Regarding the three observed floods, in all the grain-size classes there are pebbles that hardly moved during the floods. The average distances away from the introduction point are almost alike for the grain-size classes, below to *D50*, with a slight rise with the increase in phi and a sharp decrease when phi is greater than *D50*. There is similar behaviour, though less accentuated, in the maximum distances.

The correlation between bed load transport obtained experimentally in natural rivers and hydraulic parameters such as discharge are much lower than expected (Billi & Tacconi, 1987). The variability of coarse sediment transport is very high and is characterized by pulses that have been both to morphological-sedimentary features of the river bed and to variations in discharge (Klingeman & Milhous, 1970; Hayward & Sutherland, 1974; Meade *et al.*, 1981; Reid *et al.*, 1985; Tacconi & Billi, 1987).

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