Incipient Bed-Material Motion in a Gravel-Bed River: Field Observations and Measurements

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Abstract

Patches of fine sediment control the incipient motion of bedload material in gravel-bed rivers. As well as being fundamental in fluvial dynamics, agitation and eventual downstream movement of bed material is of ecological relevance as it can trigger mass drift of benthic invertebrates. However, bedload studies have largely neglected the process of incipient motion, primarily due to technical constraints on sampling. Here we report on the results of a series of field experiments using a portable flume which, in combination with measurements from slot samplers i.e. traps allows assessment of bedload characteristics at the very beginning of flow events when bedload is marginal. Maximum shear stress generated by manipulations of the flume was 40 N/m^2. Flume data indicate that bed material agitation and subsequent transport occurred once shear stress reached a threshold of 1 N/m^2. The force necessary to entrain material from patches was much higher than that predicted by the Shields equation, presumably reflecting a hiding effect. Flume bedload rates were extremely low (80% of values were less than 1 g/sm) and rather variable. In turn, significant bedload (i.e. >1 g/sm) was detected in the traps once shear stress reached 30 N/m^2. Combined results from flume and traps indicate two phases of bedload transport from patches: the first is dominated by sand and a second is dominated by fine gravel. A third phase occurs, but this involves most surface material from the reach contributing to bedload. The relative scarcity of sand in the traps indicates that the traps were largely incapable of detecting the first phase of bedload transport. While the flume helps to describe the incipient motion of material prior to conditions when traps are able to detect transport, the traps yield data on bedload at shear stresses greater than those generated in the flume. Thus, combining data from the flume and traps provides a clearer view of bedload transport during the very early stages of flow events.

Keywords: bedload transport, bed-material entrainment, patches, gravel-bed rivers, field experiments, portable flume, Reid slot sampler, Ribera Salada, Ebro basin

1. INTRODUCTION

Incipient bedload transport in armoured gravel-bed rivers is often controlled by patches of fine sediment (e.g. Garcia *et al.*, 1999). At the very early stages of a given flow event, three pre-bedload flux phases of motion have been identified as occurring in patches (Garcia *et al*., 2007). The three phases are associated with very low bedload transport rates (i.e. marginal transport). These rates being very sensitive to changing hydraulic conditions (Church and Hassan, 2005); bed material moves only partially and thus entrainment is size-selective (e.g. Wilcock and McArdell, 1993). Due to technical and operational constraints on sampling, such low transport rates are often difficult to detect by traditional bedload devices (e.g. because of problems of perching and blocking in the case of the Helley-Smith sampler (Vericat *et al.*, 2006) and the problem of the relatively high detection threshold in the case of the bedload pit-traps). Thus, assessment of the controls on bed-material entrainment at the very early stages of flow events has been frequently neglected in bedload transport studies.

Bedload transport in gravel-bed river channels typically falls below the conventionally adopted threshold condition (Church and Hassan, 2005). In addition, bedload transport during the initial phase departs dramatically from predictions obtained by means of classical formulae. Although of limited impact on river channel morphology, bed-material agitation in patches and its subsequent transport are of great biological importance, since they can trigger mass drift of stream invertebrates, thus causing disturbance to benthic communities (Gibbins *et al.,* 2007a; 2007b). Few attempts have been made to characterise bed-material entrainment and transport under very low transport rates in natural river conditions. This paper examines the relations between hydraulic conditions and bedload rates as well as bedload grain-size in a gravel-bed river during the very early stages of flow events when transport rates are very low. To assess these relations we conducted a series of field experiments in the Ribera Salada (Ebro basin, NE Iberian Peninsula) using a prototype portable flume which, in combination with three Reid slot samplers (previously termed the Birkbeck sampler), allowed us to assess bedload transport characteristics from the very beginning of rises to the point when the breakup of the armour layer occurs and the channel becomes unstable at the reach scale. Results from the Ribera Salada are discussed in the light of those obtained in the nearby Upper Tordera River under similar physical conditions (i.e. Garcia *et al*., 2007). Comparisons allow generalisations about the controls on incipient motion during the early stages of flow events in gravel-bed rivers.

2. STUDY AREA

Field experiments were carried out in a reach of the Ribera Salada, an unmodified upland gravel-bed river located in the Catalan Pre-Pyrenees (Figure 1). Flume experiments were conducted between January and April 2006 over a 140 m length of channel and included manipulations in riffle, pool and plane bed areas. The bed slope at the study reach is 0.009. The study reach has an estimated median discharge (Q_{50}) of 1 m^3/s and a Q_{10} of 3 m^3/s (for details on flow measurements see Batalla *et al.,* 2005). The median surface sediment size ($D_{50\text{-}s}$) in the reach is 49 mm (Figure 2a) while the median subsurface ($D_{50\text{-subsurface}}$) is 24 mm. The river-bed armouring ratio ($A_r = D_{50\text{-surface}}/D_{50\text{-subsurface}}$) is 2; thus the river-bed in the study reach can be described as being armoured.

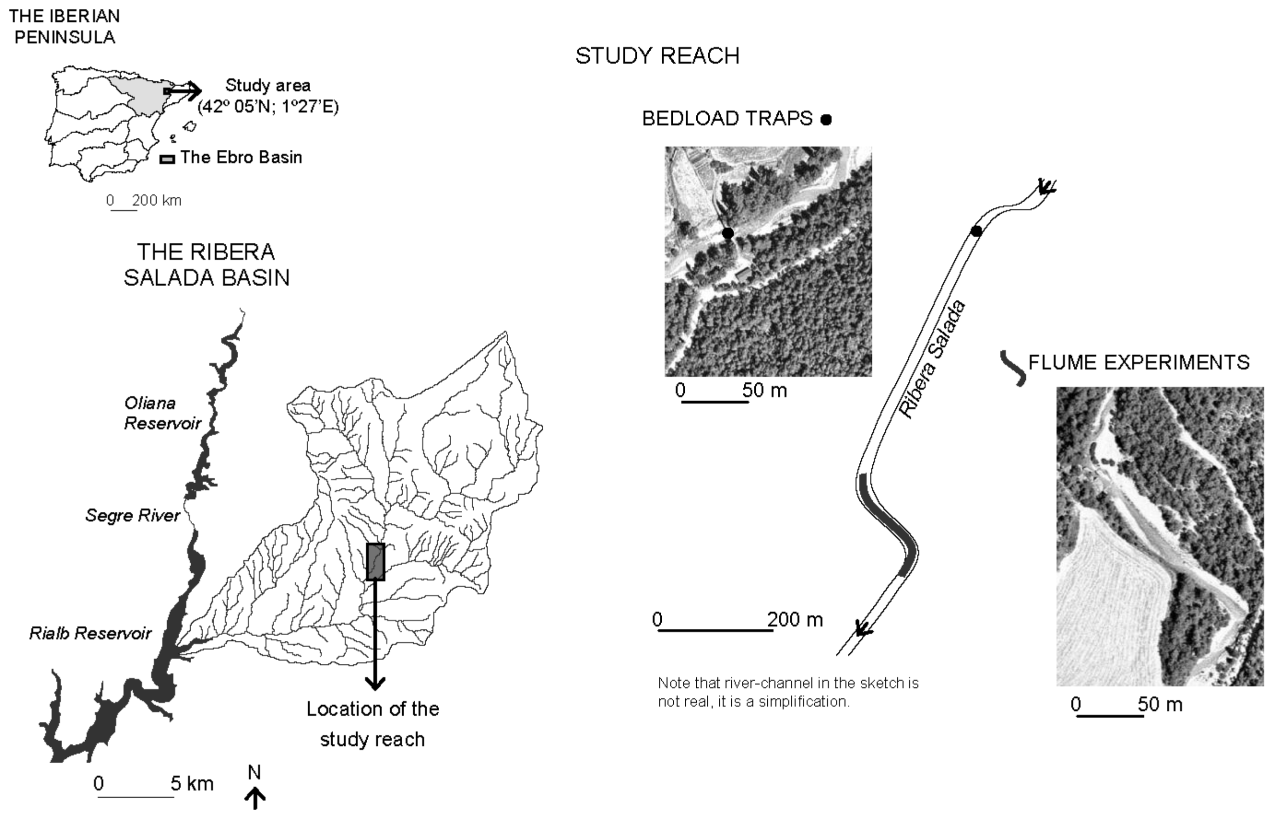

Figure 1. The study reach in the Ribera Salada in the context of the middle River Segre. The site where flume experiments were undertaken and the location of the bedload traps are shown.

The term 'patch' is used to characterize river-bed structures of varying size and shape (e.g. Mosley and Tindale, 1985). In this study we use the term to refer to fine-texture sediment accumulations usually located behind obstacles or in depressions in the river-bed (Laronne *et al*., 2001, Figures 2a and 2b). Patches in the study reach cover between 10% to 20% of the river-bed surface and fall in the micro-patch category as described by Church and Hassan (2005). These patches are the principal source of sediment during the early stages of flow events, and are the dominant source of material transported during small and frequent flow events (Garcia *et al*., 1999), the hydraulics of which we recreated inside the flume. In our study reach, Batalla *et al*. (2005) reported that the average median size of the bedload samples ($D_{50\text{-bedload}}$) measured with a Helley-Smith sampler closely resembles that of the patches ($D_{50\text{-patch}}$), and it is finer than the $D_{50\text{-surface}}$ and $D_{50\text{-subsurface}}$ of the whole reach.

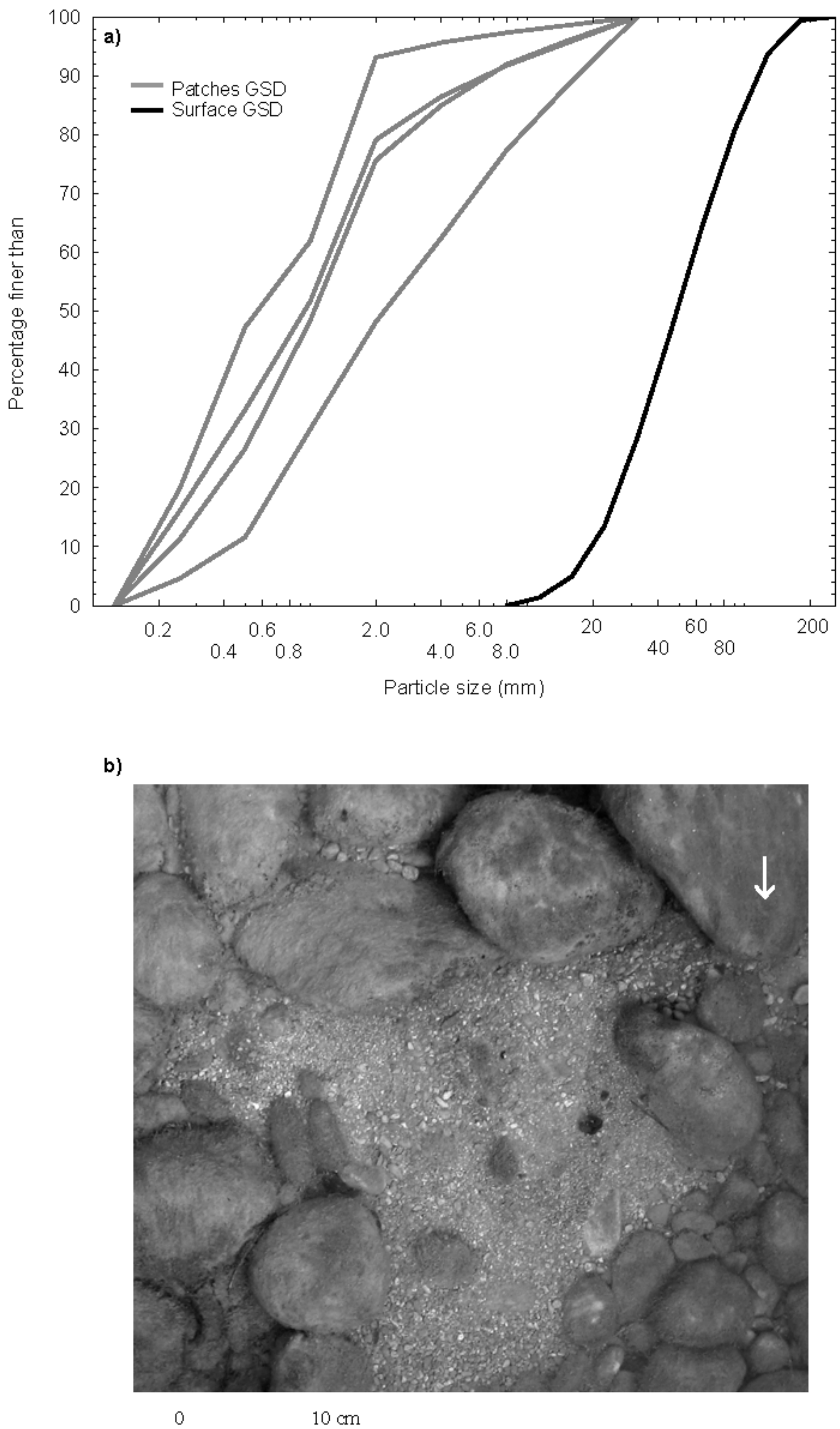

Figure 2. a) Grain-size distributions (GSDs) of the patches and the surface material in the Ribera Salada experimental reach (redrawn from Gibbins *et al*., 2007b), b) A micropatch of sand and granules in the Ribera Salada, as typically found in many other gravel-bed rivers (arrow in the plate shows flow direction).

3. METHODS

3.1. Bed-material sampling

Sediments in patches were sampled in January 2003 using the area by weight method (Kellerhals and Bray, 1971). No significant flow events occurred in the Ribera Salada between the patch sampling and the flume experiments. Surface material was sampled in December 2005 using the pebble count method (Wolman, 1954), with a total of 500 particles from the reach measured at ½ ϕ intervals (Figure 2a).

3.2. Experimental design

Experiments using the flume were undertaken in the early spring 2006. In total, experiments were undertaken at 30 locations across the study reach. Once placed on the river bed, the flume (Figure 3a) isolated a target patch of fine material (i.e. sand and fine gravel). Flume dimensions meant that manipulations (see below) impacted a 0.5 m^2 area of bed. An elevation in the water depth of 1 to 2 cm was observed within the flume walls. The elevation was constant throughout the flume and no depression in the water surface was observed. Measurements of hydraulic conditions and associated bedload transport were made with the flume doors in their normal position (parallel to the main flume wall) over a 15-minute period. All measurements of velocity were made using a Valeport Electromagnetic flow meter Model 801. Mean velocity and standard deviation (hereafter SD) were recorded over a 1-minute sampling duration. Hinged doors at the upstream end of the flume allowed more water to be funnelled into the flume; this had the effect of increasing velocities and, when shear stress was sufficiently high, mobilizing bed material (see Vericat et al., 2007 for more details on flume characteristics). These doors were then opened for a period of 5 minutes to assess any changes in bedload. Velocity was again measured during this period of flow manipulation. Bedload material was captured using a 1 mm mesh net fixed to the downstream end of the flume (Figure 3a, see Gibbins *et al.*, 2007a and 2007b for more details on sampling procedures).

Figure 3. Experimental and measuring devices: a) portable flume (for more details see Gibbins *et al.*, 2007b) and b) Birkbeck-type bedload traps in operation since November 2005. Inset plate in b) shows an aerial view of the traps full of sediments after the 2006 July and August flow events. Arrows show flow direction, while in b) flow direction is from the top to the bottom of the plate.

Several issues arise from flow convergence in the throat of the flume as a result of the use of the doors. Discharge increases within the flume walls, so streamflow-lines over a patch of channel are not the same as those existing there prior to the flume being positioned. This alteration was essential, as otherwise it would not be possible to achieve the conditions under which bedload transport occurred. Flume walls were very thin (1 cm) and made of light, smooth material so as to minimize flow disturbance. Nevertheless, the angle of the doors, once opened, could lead to eddy-shedding and, hence, increasing near-bed turbulence within the parallel section of the flume. Moreover, transverse energy exchange was cut by flume walls, because they isolate the interior of the flume from the rest of the streamflow. No empirical data are available to allow assessment of these effects. The surface profile and the water depth within the 1m long flume was constant during the experiments, suggesting that no flow acceleration occurred; this suggests a steady flow over the fine sediment patch. The 1-minute replicate velocity measurements made at 0.2 and 0.4 of the depth during all the experiments yielded very similar values (i.e. ratio between first and second measurements average 0.98; SD=0.09). This also suggests constant flow conditions within the flume walls over the entrainment zone and across the range flow conditions created by the manipulations.

Particulate Organic Matter (hereafter POM) was not a major component in the samples. Experiments were conducted in the early spring, a time when there is very little POM in the stream i.e. leaf-fall from deciduous trees occurred several months prior to the experiments and had already passed though the system on autumn and early winter high flows, while periphyton growth on stones was negligible. Nets were continuously inspected for POM transport during experimental trials and very little fine or coarse material was found, even at longer sampling durations. Thus, there was no concern over the potential clogging of the sampling net by POM. The ratio between velocity measurements replicated during each trial was almost 1, indicating that backwater effects due to progressive net clogging by POM did not occur.

Bedload samples collected during the flume experiments were dried, sieved and weighed to obtain a total weight and grain size distribution (hereafter GSD) for each sample. In order to avoid errors due to under-measurement of sand, bedload-sample analyses were truncated at 1 mm according to the mesh diameter of the net. The mean ratio between the truncated and untruncated bedload rates is 1.37 (SD=0.30), indicating that estimated rates were not markedly affected by truncation.

In conjunction with opening the hinged doors, a Perspex sheet was slid vertically into the flume. At each location, the flume was positioned so that this sheet was at the upstream end of the target patch fine material. The sheet slid into a fixed position, leaving a gap of 15 cm between the bottom of the Perspex and the stream bed. The Perspex partially dammed the water funnelled into the flume by the doors, with the pressure from upstream forcing water through the gap and generating a nearbed jet of water over the target patch. No hydraulic jump was observed. This jet was responsible for the high velocities and shear stresses necessary for bedload movement. Once positioned at the start of an experiment, the Perspex sheet remained unmoved. Thus, the jet created by the Perspex sheet was relatively stable for the period of experimentation at each patch location.

The jet disrupted the vertical velocity profile inside the flume. For this reason, it was not possible to calculate shear stress using the velocity profile. Instead, the local boundary shear stress was calculated using the formula developed under similar test conditions by Whiting and Dietrich (1990):

$$\tau_b = \rho\ (v_z\ k)^2\ [\ln\ (10z/D_{84})]^{-2}$$

where, τ_b is the local boundary shear stress in N/m^2, ρ is the fluid density in kg/m^3, v_z is the flow velocity at height z above bed in m/s, k is the von Karman's constant (equal to 0.4), z is the height above bed in m and D_{84} denotes the 84 percentile (in mm) of the surface GSD. Velocity measurements used in the calculations were made at 0.2 of the depth, fulfilling the recommendation of Whiting and Dietrich (1990). This formula was subsequently tested by Whiting and Dietrich (1991) in a stream where conditions were similar to the flume (increased nearbed velocity, with little variation through the vertical profile and similar roughness). They found that in these conditions it yielded more reliable results than using the vertical profile. For more details of experimental procedures see Gibbins *et al.* 2007a, 2007b.

Velocities and the rates of bedload transport approximated those which occur during flow events of around 5 m^3/s in the study reach (e.g. January and April 2006 flow events). Events of this magnitude occur frequently (discharge equalled or exceeded around 5% of time), indicating that the patches of fine sediment regularly become unstable and subsequently entrained.

3.3. Bedload traps

Three Reid slot samplers for bedload were installed in the Ribera Salada in November 2005, each having a capacity of 0.22 m^3 (Figure 3b). The cross-channel slot width has a variable opening, which we held constant at 0.20 m. The streamwise length of the slot is 0.4 m, approximately ten times the $D_{50\text{-surface}}$. Bedload and water depth are recorded every 5 minutes. The design of the bedload traps was based on previous work by Garcia *et al.* (2000). Each box includes a side-wall door to identify changes in bedload texture (i.e. Kunhle 1992, Bergman *et al.*, 2006). Since installation, four sub-bankfull flow events were monitored (January, April, July and August 2006 (Figure 4).

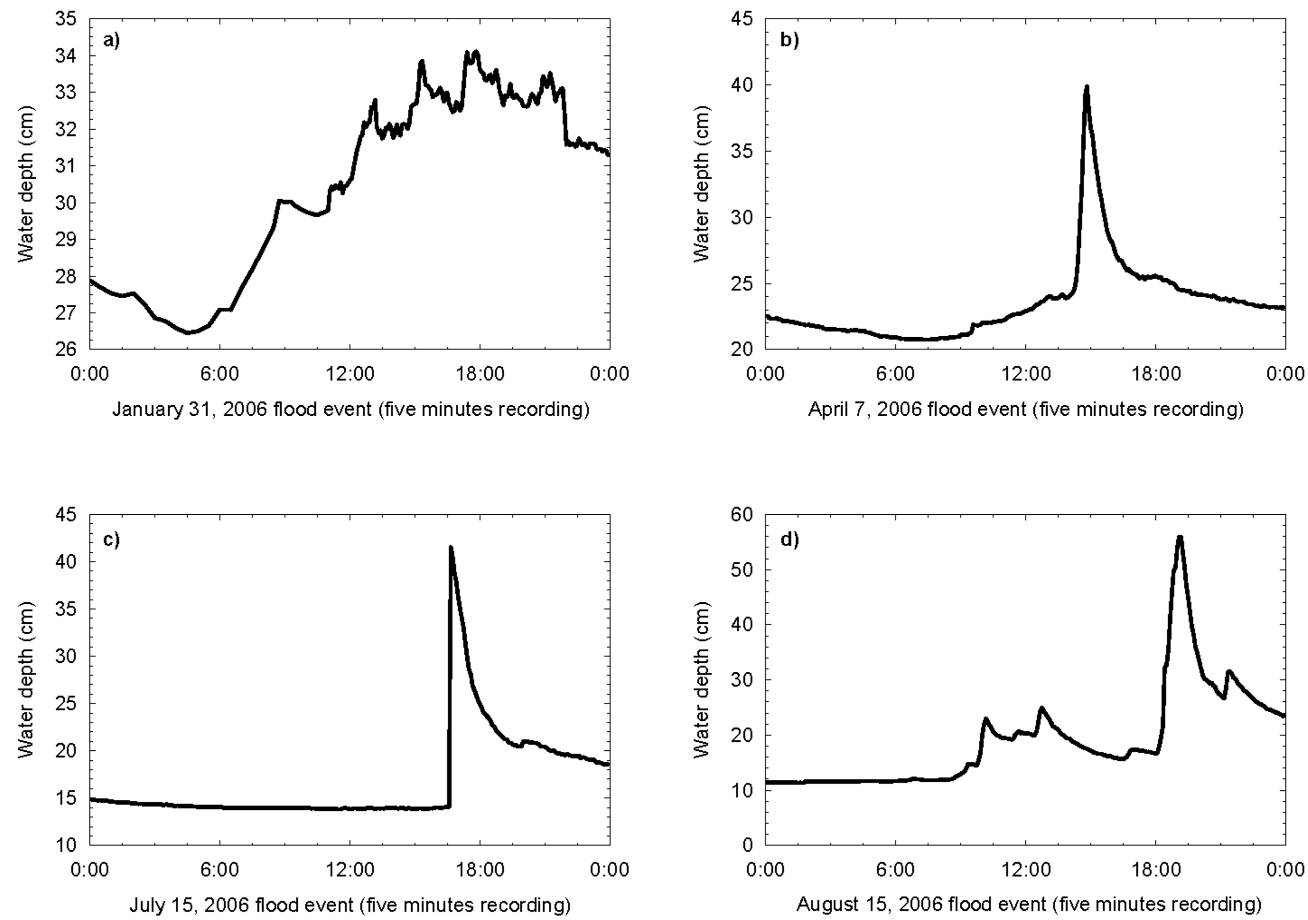

Figure 4. Flow hydrograph (water depth recorded every 5 minutes) of the Ribera Salada obtained at the bedload transport monitoring station during 2006 flow events: a) January, b) April, c) July and d) August. Mean water depth during 2006 was 15 cm.

4. RESULTS AND DISCUSSION

River-bed sediments can be rather active before classical bedload monitoring devices (i.e. bedload traps) detect movement. Our observations during the 30 flume experimental runs showed bed-material agitation in patches and subsequent downstream movement once shear stress reached a threshold value of 1 N/m^2, although bedload rates were extremely low (i.e. i_b ~ 0.01 g/sm). However, values varied markedly between experimental locations due to the particular conditions of river-bed sediments and patch characteristics. For instance, zero bedload rates were measured in six locations even under shear stress values greater than 1 N/m^2, and four other measured rates were lower than 0.01 g/sm (the latter were excluded in the subsequent analysis). All the observed transport rates were extremely low with 80% of our values falling below 1 g/sm. A similar range of results was reported by Church and Hassan (2005); in their stream (Harris Creek) bedload was not detected until shear stress exceeded 15 N/m^2. Mean shear stress and bedload rate during the Ribera Salada experiments were 10.3 N/m^2 (SD=9.9 N/m^2) and 0.75 g/sm (SD=1.48 g/sm), respectively (complete database is presented in Table 1).

Significant bedload (i.e. $i_b \cong 1$ g/sm) was detected in the traps at a shear stress of around 30 N/m^2. Mean shear stress and bedload rate during the four small flow events monitored in 2006 were 41 N/m^2 (SD=7.4 N/m^2) and 438 g/sm (SD=396 g/sm) respectively (Table 1).

Sediment entrained during experiments was mostly sand ($D_{50\text{-bedload (experiments)}}$=1.7 mm, SD=0.33 mm) while that found in the traps was mostly gravel ($D_{50\text{-bedload (traps)}}$=10.9 mm, SD=4.0 mm), with sand also present. The data suggest two phases of bed-material transport from the patches: an initial one dominated by sand (i.e. general transport), followed by another dominated by fine gravel (i.e. size-selective transport), both of them characteristic of the threshold channels (see Church, 2006). Our results corroborate previous results reported by Wathen *et al.* (1995) in the Allt Dubhaig and by Church and Hassan (2005) in Harris Creek, amongst others. In the Ribera Salada the two phases would have been difficult to define with data from the traps only; sand represents less than 10% of captured material during July and August 2006 flow events and 16% during the April event. Only during the event in January 2006 did the traps capture a significant amount of sand (30% of the total load). When the hydrograph is relatively steep (i.e. April flow event in relation to January) sands are rapidly suspended at the very beginning of the event (within 5 minutes or less) and traps do not capture them. Consequently, incipient bed-material entrainment from patches is unrecorded.

Table 1. Database of the flume experiments and the pit-trap measurements in the Ribera Salada experimental reach.

Flume samples (code)	Shear stress (N/m^2)	Bedload rate[1] (g/sm)	Grain size	
			(D_{50}, mm)	(D_{95}, mm)
L1V2a	1.8	0.08	1.5	**3.1**
L2V2a	7.4	<0.01[a]	-	**-**
L3V2a	3.9	0.01	1.5	**3.1**
L4V2a	6.6	0	-	**-**
L5V2a	11.2	0.24	1.6	**3.9**
L6V2a	10.8	0.08	1.5	**3.2**
L7V2a	9.1	0.02	1.5	**3.1**
L8V2a	8.9	<0.01[a]	-	**-**
L9V2a	6.2	<0.01[a]	-	**-**
L10V2a	1.0	0.01	1.5	**3.2**
L11V2a	7.9	0.01	0.9	**1.3**
L12V2a	0.2	0	-	**-**
L13V2a	1.1	0	-	**-**
L14V2a	13.0	0.02	2.5	**7.3**
L15V2a	7.4	<0.01[a]	-	**-**
L16V2a	9.3	0.46	1.5	**3.8**
L17V2a	18.2	0.41	1.5	**3.4**
L18V2a	12.8	0.21	1.6	**3.9**
L19V2a	25.0	1.46	1.7	**7.3**
L20V2a	19.6	3.65	1.8	**11.7**
L21V2a	40.6	3.66	1.9	**20.9**
L22V2a	33.7	5.20	1.8	**16.4**
L23V2a	24.6	4.30	2.0	**7.7**
V1 flume	1.2	0	-	**-**
V2 flume	4.6	0.01	1.7	**3.9**
V3 flume	1.8	2.31	2.1	**6.5**
V4 flume	3.6	0	-	**-**
V5 flume	3.4	0.34	1.6	**3.6**
V6 flume	1.2	0	-	**-**
V7 flume	12.0	<0.01[a]	1.4	**1.9**
Pit-trap samples (2006 flow events)				
January	29.0	0.98	2.9	**14.6**
April	35.0	0.77	5.7	**27.8**
July	38.0	629.2	10.1	**36.7**
July	34.9	140.6	12.0	**33.4**
August	42.7	199.5	10.6	**42.7**
August	38.1	280.5	11.3	**35.2**
August	51.9	281.4	12.8	**57.1**
August	46.1	846.3	12.7	**44.6**
August	50.2	998.7	16.2	**56.2**
August	46.7	1001.9	15.3	**64.5**

[1] Bedload samples truncated at 1 mm (see text for details)
[a] Not used in the analysis

Mean bedload grain size during the flume experiments does not increase with shear stress, indicating that sand transport from patches is close to equal mobility. In contrast, maximum grain-size in the patches (here represented by the $D_{95\text{-bedload (experiments)}}$ of the bedload samples) is more sensitive to changing flow conditions, indicating that gravel particles tend towards size-selective entrainment ($\theta=0.19(D_{95\text{-bedload (experiments)}}/D_{50\text{-patch}})^{-0.28}$; N=8; $r^2=0.29$; $p<0.1$). The shear stress required to entrain the largest grains from the patches in the Ribera Salada diverges form the Shield's relation for uniform grains, indicating that more force is needed (5 times on average) to entrain particles. Presumably, this reflects the role of the hiding effect (Fenton and Abbott, 1977). This is clearly demonstrated by observations during flume experiments and corroborated by trap data from the small rise that occurred in January 2006 (Figure 5). Our relation and the Shields' relation cross near the $D_{50\text{-surface}}$ (≈50 mm) at the point when equal mobility for gravel would occur. Coarser sedimentary material (as suggested by data from August 2006 flow event) would entrain at smaller forces than Shields' relation predicts as a result of its relatively high exposure in the river-bed. Similar results were reported by Church and Hassan (2005).

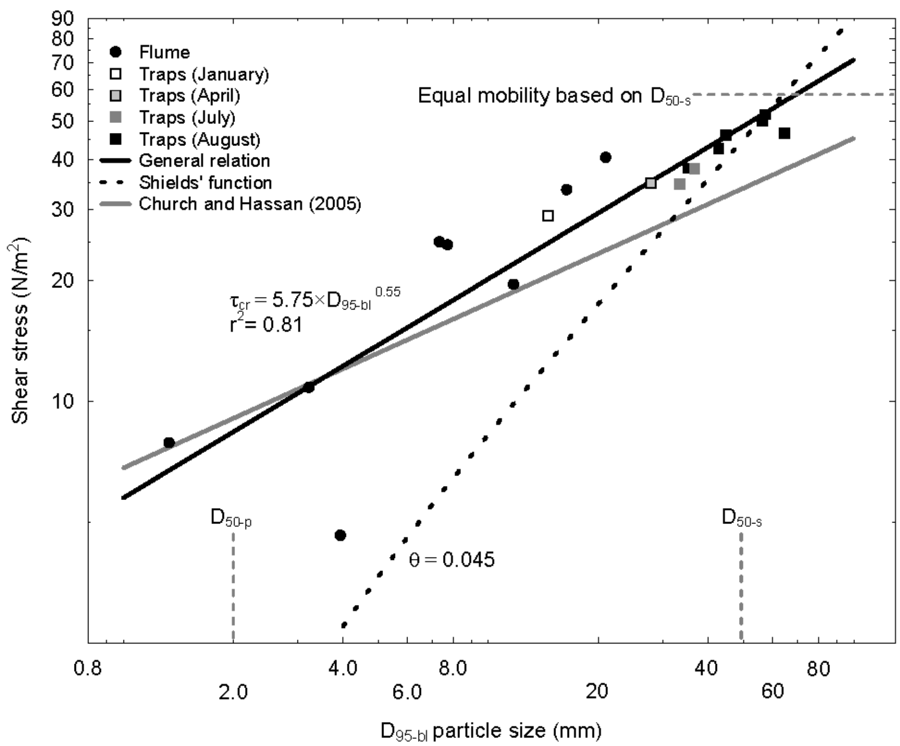

Figure 5. Relation between shear stress at entrainment and maximum grain-sizes (designed by the $D_{95\text{-bl}}$) for different field conditions in the Ribera Salada (equation presented in the figure). Shear stress data is grouped according to eight grain-size fractions at 1 mm interval; data from traps represents average values obtained at the 3 traps in the monitoring station. Shields' function modified for sediment mixtures (θ = 0.045) is given. Field data from Church and Hassan (2005) in Harris Creek are shown for comparison. $D_{50\text{-p}}$ and $D_{50\text{-s}}$ denote median sediment sizes in patches and riverbed surface, respectively.

The $D_{50\text{-bedload (experiments)}}$ shows a weak correlation with bedload transport, once more inferring the equal mobility for sand transport during early stages of bed-material entrainment (Figure 6). This means that once sand grains in the patches are agitated by increasing hydraulic forces they move downstream (mainly in saltation) independently of their size. We did observe within-patch grain instability, giratory step-and-rest motion before net downstream transport in the flume, as has been identified through a series of video experiments in the Upper Tordera (Garcia *et al.*, 2007). Under such conditions mean bedload size is very similar to mean bed-material size of the patches (Figure 6). Only at higher shear stresses does bedload grain-size increase with bedload rates, reflecting the progressively higher presence of gravel in transport; this represents a departure from the size range of bed-material present in the patches. In relation to this phenomenon, we observed agitation and entrainment of gravel in the flume when the sand was already undergoing general transport.

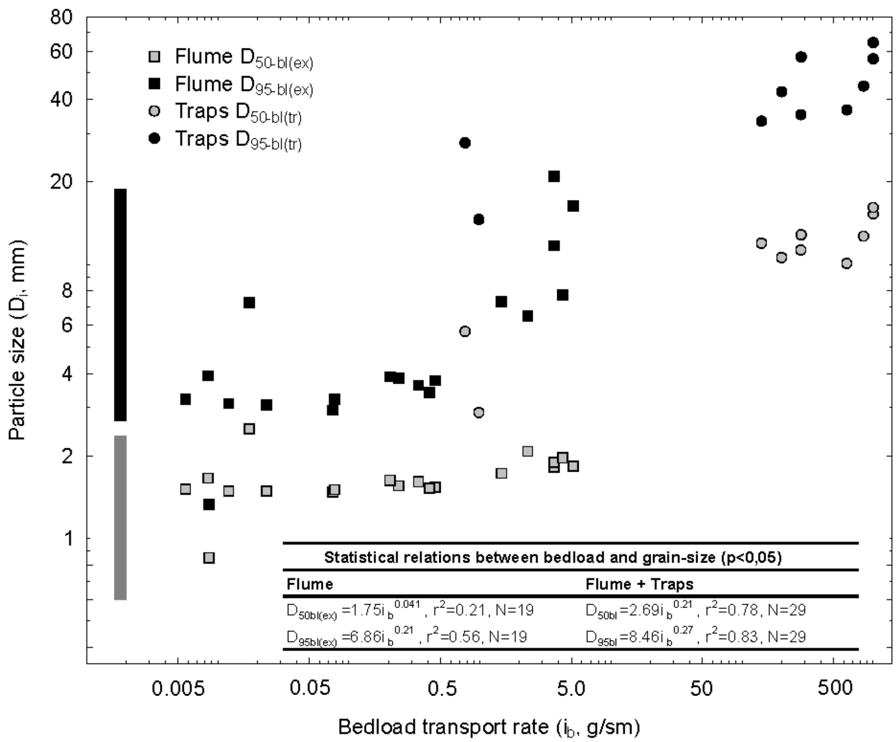

Figure 6. The relation between bedload grain-size (designed by the $D_{50\text{-bl}}$ and $D_{95\text{-bl}}$) and bedload transport rates obtained during flume experiments (ex) and from the bedload traps (tr) installed in the Ribera Salada, with statistical relations given in the table. Vertical strips indicate the range of median (in grey) and maximum (in black) particle sizes sampled in patches of the river-bed (see Figure 2).

In contrast, maximum grain-size of bedload shows a strong correlation with bedload transport rates. The relation becomes stronger once flume and trap data are plotted together (Figure 6). The relation between the range of maximum grain-size of bedload and the range of maximum grain-size of the patches indicates that coarse particles typically not found in patches clearly contribute to bedload transport under greater hydraulic forces (i.e. July and August 2006 flow events). Under such circumstances the rate of change of grain-size with transport becomes much more sensitive than it is under low-transport conditions, since a rapidly increasing proportion of the bed area is involved in the process (i.e. subsurface sediment supply and armour instability).

5. FINAL REMARKS

Field experiments and measurements of bed-material entrainment and transport carried out in the Ribera Salada point to the distinct sequence of sand and gravel mobility in the patches of fine sediments typically present in gravel-bed rivers. This field experimental research confirms the nature of the initial bedload flux from river beds that are natural and water-lain and complements studies carried out in the Upper Tordera which described patch- and grain-scale processes related to the initiation of bedload motion (Garcia *et al*., 2007). Fine-grain patches are the most important source of sediment during the early stages of rises and, overall, during small (less than bankfull) flow events. Once the bed-material begins to agitate, the sand particles move downstream independently of their relative size (i.e. overpassing phase, see Ashworth and Ferguson, 1989); when the sand from the patch is fully mobilized, gravel begins to agitate and is eventually transported, showing a distinctly size-selective entrainment behaviour (the size-selective phase of Komar, 1996). In both cases, the force necessary to entrain sediment is much higher than that predicted by the Shields relation ($\theta= 0.045$). Equal mobility for river-bed sediments may occur when other parts of the streambed become progressively unstable (armour layer) and active (subsurface sediments), so that all the local bed material participates in transport (the fully-mobile phase; see Jackson and Beschta, 1982). In the case of the Ribera Salada data, this occurs when the $D_{95\text{-bedload}}$ *vs* τ relation and the Shields' relation cross, near $D_{50\text{-surface}}$. Insufficient data are available at the moment to illustrate a tendency beyond the crossing point in Figure 5. As stated by Church and Hassan (2005), the result saves the practice of using the $D_{50\text{-surface}}$ as the reference grain-size for entrainment estimates.

Agitation and mobilization of sediments in patches (i.e. overpassing phase) can trigger mass drift of stream invertebrates (Gibbins *et al.*, 2007a; 2007b). Within this context, the portable flume, despite its current prototype design, has proved to be a reliable and simple technique for field examination of process involved in the onset of bedload transport, as well as associated biological responses. Thus, it can yield data fundamental to understanding and modelling bedload transport and associated fluvial dynamics in river channels and helps bridge the gap between geomorphological and ecological process studies. Combined data both from the flume and the Reid slot samplers allows a clearer view of long-term eco-geomorphological processes involved in the early phases of bed-material entrainment and transport. The flume helps describe incipient motion of bed-material prior to the point when traps are able to detect bedload; in turn, trap values represent the upper end of τ-i_b relations that the flume can recreate under its current design. Both techniques cannot be compared for short-term bedload variability because, unlike the traps, the flume does not give information of at-a-section temporal variability i.e. flume experiments are independent 5-minute trials performed at different sites within a study reach that cannot be temporarily correlated.

Sand moves in saltation as well as in contact with the river-bed. During saltation, a high proportion of sand grains are likely to overpass pit-trap slots. If this occurs, traps may not capture and hence be unable to register such transport. Our observations indicate the need for design modifications to the bedload intakes of the traps in order to improve their efficiency in capturing sands moving during periods of marginal bedload transport and especially transient periods early during the sharply rising limbs of flood hydrographs. This is of great significance in gravel-bed rivers, which have a significant proportion of their beds comprising patches of fine sediment. We are currently working to overcome this problem by modifying the downstream end of the aperture of the pit-trap slots in such a manner that they capture saltating material which then falls into the traps.

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