Dependence of sediment sorting on bed-load transport phase in a river meander

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Abstract

It is widely recognized nowadays that there are at least two different phases of bed-load sediment transport in gravel-bed rivers. However, the transition between these phases is still poorly or subjectively defined, especially at bends in rivers, where cross-stream sediment transport can strongly influence changes in the texture of the transported sediment. In this paper, we use piecewise models to identify objectively, at two points in the cross-section of a river bend, the discharge at which the transition between bed-load transport phases occurs. Piecewise models were applied to a new bed-load data set collected during a wide range of discharges while analysing the associated changes in sediment texture. Results allowed the identification of two well-differentiated phases of sediment transport (phase I and phase II), with a breakpoint located around bankfull discharge. Associated with each phase there was a change in bed-load texture. In phase I there was non-dominance in the transport of fine or coarse fractions at a particular sampling point; but in phase II bed-load texture was strongly linked to the position of the sampling point across the channel. In this phase, fine particles tended to be transported to the inner bank, while coarse sizes were transferred throughout the middle parts of the channel. Moreover, bed-load texture at the inner sampling point became bimodal while the transport of pebble-sized particles was increasing in the central parts of the river channel. It is suggested that this general pattern may be related both to secondary currents, which transfer finer particles from the outer to the inner bank, and to the progressive dismantling of the riverbed surface layer.

Key words: bed-load texture, piecewise regression, sediment transport phases, river bend, large River.

Introduction

It is generally recognized that the surface of the riverbed in most gravel rivers is considerably coarser than the subsurface sediment, and that the particle-size distribution in the surface and subsurface layers results from a complex interaction between flow hydraulics, sediment fluxes and river channel morphology. Development of a coarse surface layer has been attributed to three distinct mechanisms (Bunte & Apt, 2001): (1) selective scour of fine particles; (2) selective deposition of large particles, and (3) armouring, which occurs when sporadic high flows mobilize large particles. Irrespective of the formative process, it is clear that the presence of a coarse surface layer determines the nature of sediment transport by both restricting bed-load transport rates and limiting the supply of fine material from the subsurface to the bed-load. This buffering effect diminishes when a water discharge occurs that is able to dismantle the armour (Ryan et al., 2005).

The general behaviour of armoured gravel-bed rivers has led to the identification of three distinct phases in bed-load transport, though any given river might not exhibit all phases (e.g. Barry, 2007). Phase I is typically characterized by the mobilization of fine sediments travelling over a largely immobile armour layer during low flows. Phase II is characterized by the transport-limited movement of surface and subsurface material during low to moderate flows (depending upon the degree of channel armouring) (e.g. Wilcock & McArdell, 1997). Phase III is characterized by a levelling off in the bed-load transport intensity at moderate to high flows. Transition from phase I to phase II indicates disturbance and initiation of transport of grains constituting some portion of the armour layer and so the bed-load includes material from both the bed surface and the subsurface stratum (Ryan et al., 2005). Conversely, the cause for the phase II/III transition is uncertain and may indicate that (Barry, 2007): 1) the flow is transporting sediment near capacity, 2) the flow has reached bankfull stage, with additional discharge spreading across the floodplain, rather than continuing to increase depth and transport rate, or 3) all available sediment sources have been accessed by the flow, such that further increases in discharge do not result in large increases in transport. While the existence of these transport phases in gravel-bed rivers is well recognized, their identification is still poorly or subjectively defined. For instance, some authors have commonly used the bankfull discharge as a first approximation to define the transition between phase I and II (Buffington, 1995; Ryan et al., 2005), but there is insufficient evidence to indicate the validity of this choice.

In the last decades, several authors (e.g. Ryan et al., 2002; 2005; Ryan & Porth, 2007) have shown the usefulness of piecewise regression models to identify objectively the discharge at which the transition between different bed-load transport phases occurs. This statistical analysis recognizes the existence of different transport relationships for different ranges of flow, inasmuch as each phase in bed-load transport shows markedly different statistical parameters (e.g. slope and variance of the regression model) and sedimentological features (e.g. changes in bed-load texture) (e.g. Emmett, 1999; Ryan & Emmett, 2002; Ryan & Porth, 2007). However, the piecewise regression model has essentially been tested in coarse-gravel mountain streams (e.g. Emmett & Ryan, 1999; Ryan et al., 2005), not in the channel bends of large rivers, where associated changes in bed-load texture have also received little attention (e.g. Dietrich & Smith, 1984; Clayton & Pitlick, 2007). Indeed, the changing nature of the transport processes associated with the evolution of bed-load grain-size distributions has been most extensively investigated under laboratory conditions (e.g., Kuhnle, 1989; Wilcock et al., 2001; Ferrer-Boix & Hassan, 2014). Field measurements are less frequently undertaken, mainly due to difficulties in covering a wide range of conditions from incipient motion to full mobilization, the dangers and problems of sampling underwater, and the high economic cost of conducting this type of sampling (Powell et al., 2001). Consequently, detailed field investigations of changes in bed-load texture with varying hydraulic conditions have been limited (e.g. Milhous, 1973; Wathen et al., 1995; Habersack & Laronne, 2001), especially in gravel-bed river bends (examples of the few studies made are Clayton & Pitlick, 2007; Clayton, 2010; Nuñez et al., 2017).

The sediment sorting effects of flow in river bends has long been recognized from the spatial distribution of bed material: coarse size fractions are more abundant in the outer region of a bend while fine size fractions are more frequent inward, over the bend point bar (e.g. Parker & Andrews, 1985). This pattern is related to the differential routing of grain sizes, controlled by near-bed shear vectors and cross-channel and downstream bed slope (e.g. Parker & Andrews, 1985; Julien & Anthony, 2002). Near-bed shear vectors are determined by the distribution of downstream flow velocities, which in bends are strongly related to a cross-stream motion, often described as a three-dimensional helical flow, induced by the curvature of the channel and affected by the width-to-depth ratio (da Silva, 2015; Termini & Piraino, 2011). Accordingly, changes in the width-to-depth ratio related to flow stage may affect the characteristics of the cross-stream motion (Dietrich & Whitting, 1989) and thus lead to changes in the local bed-load texture. Nevertheless, it is not clear if, in contrast to straight reaches, these changes might prevent the occurrence of distinct sediment transport phases in river bends.

The objective of this work was to identify and characterize phases of sediment transport in river bends. We carried out a field study in the lowermost reaches of the Ebro River, across the end of a bend in the river (Fig. 1a), in order to: 1) objectively identify and define the existence of different phases of sediment transport by means of a piecewise regression analysis; and 2) evaluate differences in grain size in sediment captured in the different phases we defined. We hypothesize the existence of a progressive spatial divergence of bed-load texture across the stream channel once the breakpoint between phase I and phase II is passed. In phase I, cross-sectional differences in bed-load composition are expected to be marginal or insignificant and related to differences in the local composition of the bed surface material across the channel section. In contrast, in phase II the progressive dismantling of the superficial armour layer (which allows the suspension of fine particles from the subsurface layer) and the increasing intensity of secondary helical flow (which sweeps finer grains inward and coarse grains outward: e.g. Dietrich & Whiting, 1989; Clayton & Eby, 2011) lead to the emergence of transverse spatial differences in bed-load texture. At this stage, bed-load texture should be composed predominantly of sand and fine gravel in the inner regions, but predominantly gravel in the central and outer zones.

Study site

The Ebro basin, with a total drainage area of 85,550 km^2, is located in the NE of the Iberian Peninsula (Fig. 1a). The Ebro River is 928 km long and its mean annual discharge in Tortosa (42 km upstream from the river mouth) is 425 m^3 s^{-1}; corresponding to 13,400 hm^3 of water yield. At present, reservoirs located in the lower parts of the Ebro River alter the hydrology and morphology of the river (e.g. Batalla et al., 2004; Rovira et al., 2014). For instance, the mean annual water yield in Tortosa has been progressively reduced by 30% for the period 1975–1992 (Ibàñez et al., 1996), and around 40% for the last 50 years (MIMAM, 2000). Frequent floods (i.e. Q_2 to Q_{25}) have also been reduced by 25% on average (Batalla et al., 2004), and the total suspended sediment transferred to the Mediterranean Sea has dropped by over 99% during the last century (reducing from 30 x 10^6 t yr^{-1} to 0.1 x 10^6 t yr^{-1} in 2010; Rovira et al., 2015). Consequently, the river has shifted from a regime dominated by phytoplankton to one dominated by macrophytes (Ibáñez et al., 2012).

The study section was located in Tortosa (drainage area 83,093 km^2), 170 m downstream of a bend of the Ebro river (Fig. 1b) in a 116-m section that is channelized, precluding both lateral mobility of the riverbanks and overflow to the alluvial-plain (Fig. 1c). These latter features, but also the immediate forced angularity of the bend induced by the lateral walls that confine the channel (see Fig. 1b), make existing conditions in the study reach very different to those that would be found in a non-modified river meander.

On the right-bank of the study section there was a well-developed active point-bar, which was completely flooded at discharges greater than 700 $m^3 s^{-1}$. Bed surface material ranged in size from very fine gravel to small cobbles, with a median riverbed surface diameter (D_{50s}) of 19 mm. Mean hydraulic-channel slope was 0.0005. Bankfull discharge is estimated at 1100 $m^3 s^{-1}$ (based on a 1.5 years return period criterion; Batalla et al., 2004).

Methods

Data collection

Bed-load samples were collected across the river channel by means of a Helley–Smith sampler (29 kg weight, 76.2 mm inlet, expansion ratio – exit area/entrance area – of 3.22, and 0.25 mm mesh size diameter of the catch sampler bag) during four floods recorded in May 2008, January 2009, March 2010, and January 2013 (Fig. 2).

Sampling points (verticals) were established from the right bank to the left bank. The potential effects of bridge piers located in the study section were avoided by sampling downstream of the bridge (Fig. 1c). Three verticals were selected at the following distances from the inner bank: 22 m (hereafter, Inner-bank or

Ib), 56 m (Inner-bank-Centre channel or Ib-Cc), and 71 m (Centre channel or Cc). A fourth vertical (Outer bank or Ob), placed at 105 m from the inner bank, was initially considered but later discarded because the extreme flow conditions (mean flow velocity up to 2.5 m s^{-1} for a discharge of 770 m^3 s^{-1}) and the massive amounts of floating material (including wood debris and macrophytes) prevented safe sampling. In addition, the Ib vertical started to be active (in terms of bed-load transport) at 1700 m^3 s^{-1} discharge. Consequently, the number of samples collected at this point was so low that a complete analysis was not possible. Therefore, this sampling point was also eliminated.

For discharges below 1500 m^3 s^{-1}, field sampling was performed from a boat. At each vertical, the boat was moored to an anchor that was kept fixed at the same location during the sampling day. This procedure ensured that samples were always taken at almost the same points of the river section. For discharges equal to or higher than 1500 m^3 s^{-1}, samples were collected from the bridge using a mobile crane placed 8 m above water level (Fig. 1c). Sampling campaigns were performed during several days for a given flood, depending on the flood hydrograph characteristics (Fig. 2). Our sampling scheme was designed to measure how hydraulic parameters (e.g. flow velocity, water depth and channel width) change during the first stages of floods. Thus, during the first 3 days of a flood event, sampling frequency was more intense than in subsequent days. Due to technical problems, the last monitored flood was an exception and the sampling frequency was reduced.

The sampling scheme was designed to characterize the bed-load texture at each vertical. Therefore, the samples collected in this study are not the typical measures of bed-load transport, which usually rely on a composite of all sediment collected from different channel positions to obtain the mean cross-sectional transport rates. Sampling was always performed from the inner-bank to the outer-bank and always at the same verticals. Once the first traverse was finished, the second traverse was initiated starting from the first vertical next to the inner-bank. Three to five traverses were made during each sampling day. The sampling time was short enough to prevent the sampler bag from being filled to more than 50% of its capacity, keeping the sampling efficiency as high as possible. In addition, in order to capture part of the instantaneous variability of bed-load rates, two consecutive individual samples were collected at each vertical and for each traverse, so that in total, 255 individual bed-load samples were obtained during flood events. We considered as bed-load all particles transported through the lower 7.6 cm of the riverbed water column. This limit was marked by the height of the sampler, as Emmett (1979), among others, established from his work at Oak Creek (Oregon, USA).

Samples were dried, sieved and weighed in the laboratory following standard procedures (e.g. Bunte & Abt, 2001) to obtain the total mass and the grain-size distribution. Bed-load samples were truncated at a diameter of 0.25 mm, corresponding to the mesh size diameter of the bag sampler. We believe that some size fractions of the material considered here as bed-load would be transported intermittently in suspension near the bed surface under some flow conditions. It might be questionable to consider these fractions as part of the bed-load. Nevertheless, since these fractions have a large presence in the samples, excluding them from the bed-load analysis could lead to a misinterpretation of the bed-load texture changes that occurred at different transport stages (e.g. McLean et al., 1999; Habersack & Laronne, 2001).

Bed-surface material was characterized at the same points where bed-load samples were collected, including the Ib and Ob verticals as well. At each sampling point, up to 200 pebbles were obtained by means of pebble counts (Wolman, 1954) conducted in longitudinal transects in up- and downstream directions, covering an approximate area of 5 x 15 m per point. Bed particles in the wet area were collected by scuba divers at water depths ranging from 0.5 to up 6 m (Fig. 3). Particles were taken at regular intervals (~25 cm) avoiding serial correlation (Church et al., 1987). Grain sampling was truncated at 4 mm size following the standards of this method (Wolman, 1954).

Bed-subsurface material was characterized by means of bulk samples collected within the area covered by pebble counts. Bed surface particles were removed, and then the subsurface material was carefully collected using a scoop sampler, following Billi & Paris (1992), who used this method to collect river bed particles in deep water (by divers). Sample weights ranged from almost 17 kg to approximately 30 kg, with the coarsest particles making up no more than 2% of the total sample weight (Church et al., 1987). In addition, subsurface samples were truncated at 0.25 mm in order to minimize potential errors (e.g. loss of the finest particles) during sampling procedures. The subsurface GSDs were truncated at 4 mm for computing the armour degree ($D50_{S}/D50_{SS}$) of the riverbed. Particles below 32 mm were dry-sieved in the laboratory while material greater than 32 mm was measured in the field by means of a template, and then analysed for 1Φ intervals to obtain the total mass and the grain-size distribution.

Water discharge was obtained from a gauge station located 130 m upstream from the study cross-section. No significant water discharge variations were observed within each sampling day, since flow was regulated by the upstream reservoirs.

Statistical analysis

A piecewise regression model was applied for objectively defining phases of bed-load transport and the discharge at which there was a substantial change in the nature of sediment transport. The analysis was carried out by recognizing the existence of different transport relationships for different ranges of flow and sampling sites (verticals). Accordingly, bed-load samples collected at each vertical (namely, Ib-Cc and Cc) were analysed separately in two groups (each one representing different parts of the cross-section) and used to characterize the spatial variation in transport and the onset of phase II (moderately intense) transport. In addition, the two consecutive individual samples collected at each vertical and traverse were grouped into a single one. Thus, part of the inherent variability of bed-load rates was eliminated by obtaining both the mean bed-load rate of the two consecutive samples and its associated GSD.

Piecewise regression models are a suitable statistical method for situations where the response variable shows abrupt changes for small increments of the explanatory variable (Toms & Lesperance, 2003). In this type of analysis, the independent variable is partitioned into two or more intervals, and a line segment is fitted to each interval. Each line is connected with an adjacent line at an unknown value called the breakpoint, which is the value of the independent variable where the slope of the linear function changes. In analyses of bed-load, the breakpoints are interpreted as the discharges at which a change in the nature of sediment transport takes place (Ryan et al., 2002).

When there is only one breakpoint the model can be written as a continuous function at all points as follows:

$$y = a_1 + b_1 x \quad \text{for } x \leq c$$

$$y = \{a_1 + c\,(b_1 - b_2)\} + b_2 x \quad \text{for } x > c.$$

where, a_1 is the intercept of the first line segment; b_1 is the slope of the first line segment, b_2 is the slope of the second line segment, c is the value of the breakpoint in the abscissa axis (in that case, the value of the discharge at the breakpoint), and x is the value for which the ordinate is being estimated (in this case, the discharge).

The first step in applying piecewise regression to the bedload and flow data was to graph the data and then fit a nonparametric LOESS function to estimate visually where the breaks appeared to occur (Fig. 4c & d). Next, a piecewise regression model was fitted to the data set to determine the breakpoint value (the point where the fitted functions intersected), as described by Ryan & Porth (2007). This was interpreted as the transition between transport phases. Accordingly, the line fitted to flows below the breakpoint discharge (phase I) should have a lower slope and less variability than the line fitted to flows greater than the breakpoint. In contrast, the latter should have a significantly steeper slope and more variability in transport rates due to: i) the physical breakup of the armour layer; ii) the availability of subsurface material after the armour layer breaks up; and iii) subsequent changes in both the sizes and volumes of material in transport (Emmett, 1999; Ryan & Emmett, 2002). In this study, an additional factor that might have promoted a change in the slope of the fitted line in phase II was the possible existence of a secondary helical flow, producing lateral grain size sorting by transverse exchange of river-bed particles. In straight reaches, the change in slope of the transport function at the phase I/II transition depends on the degree of armouring and the amount of fine surface sediment available for transport (Barry, 2007); in river bends the change might also be affected by the intensity and direction of secondary currents, which could increase the transverse exchange of sediment.

Once the regression model had been constructed, the goodness-of-fit of the model was tested. To validate the model, the piecewise regression model was compared to a single linear function and a power function. For that purpose, the standard errors (SE) were used to compare the degree of prediction of the tested models. Statistical analyses were performed with R software 3.0.2 using the GLM function.

Comparisons between bed-load and riverbed texture were made by plotting grain-size distributions (as cumulative frequency curves) obtained at different transport intensities and contrasting them with the bed material distribution. For each sampling site, the averaged grain-size distribution of the bed-load was obtained for each 100 m^3 s^{-1} increment interval of discharge (e.g. 600-700 m^3 s^{-1}; 700-800 m^3 s^{-1}, etc.) was obtained. In addition, bed-load and bed material grain-size distributions were compared by scaling the transport rate of individual fractions (i_{bi}) with the proportion of the subsurface bed material in that size fraction (f_i) (e.g. Wilcock & Southard, 1988; Church & Hassan, 2002; Clayton & Pitlick, 2007). The values obtained were then plotted against the geometric mean of the size fraction (D_i) (Parker et al., 1982; Wilcock & Southard, 1988) for different values of discharge (Q) (Mao & Lenzi, 2007).

Results

Riverbed overview

The analysis of grain-size distributions in the riverbed (Fig. 5) showed that both the bed surface (D_{is}) and the subsurface (D_{iss}) were sorted by location, becoming coarser from the inner bank (D_{50s} ~12 and D_{50ss} ~10 mm, respectively) to the outer bank (D_{50s} ~25 and D_{50ss} ~19 mm). As expected, the bed surface was slightly coarser than the subsurface, mainly due to the large amounts of fractions <16 mm in the subsurface layer. The degree of bed armouring ($D50_s/D50_{ss}$) approached 1, clearly indicating the absence of a coarse armour layer and the loose arrangement of the bed particles (Bunte &

Abt, 2001). However, comparison of grain-size distributions in the riverbed surface revealed that the distributions were fairly similar in the inner parts of the river cross section (at the Ib and Ib-Cc sampling points) but differed from the distribution in the outer parts of the river channel (Table 1). Therefore, two well-differentiated areas emerged across the study cross-section revealing the consistent grain-sorting pattern commonly observed in bends. This pattern is induced by secondary helical flows and their interaction with the bed topography, so that fine material is preferentially directed toward the inner side of the bend and coarse material towards the pool in the outer part of the bend. Differences in the subsurface distributions were also significant (Table 1), but not as evident as in the surface layer. In fact, the two differentiated surface areas were, in part, reflected in the subsurface layer since the Cc and Ob distributions tended to be more similar (as in the Ib and Ib-Cc sampling points).

Identification of bed-load transport phases

Bed-load transport rates collected in the study section ranged from less than 1 g m^{-1} s^{-1} at the lowermost flows to up 600 g m^{-1} s^{-1} at high flow stages, giving a mean bed-load transport rate of 57.2 g m^{-1} s^{-1} for the entire cross-section and for the full range of sampled discharges. The largest individual grain sampled varied from 2.7 to 76.5 mm with non-significant differences between sampling points. Overall, transport rates depended significantly on flow stage (Analysis of the Covariance (ANCOVA); $F_{1, 130} = 238.27$; $P < 0.0001$); but differed marginally among sampling points (ANCOVA; $F_{1, 130} = 2.895$; $P = 0.091$). These differences become visible by plotting the variation of bed-load transport with increasing discharge (Fig. 4).

Visual inspection of the plot showed the typical degree of scatter related to the pulsing and unsteady nature of the bed-load processes, as well as the existence of a discontinuity in the relationship between flow and sediment. The application of the piecewise regression model indicated that the observed breakpoint was statistically significant at 899 $m^3 s^{-1}$ (± 33.8) and 925 $m^3 s^{-1}$ (± 37.3) flows for the Ib-Cc and Cc verticals, which respectively represented 82% and 83% of bankfull discharge (~1,100 $m^3 s^{-1}$). Therefore, two distinct phases of sediment transport (hereinafter designed as phase I and phase II) were inferred. In phase I, the regression slope of the fitted lines was significantly lower and with less variance than in phase II (Fig. 4; Table 2). Within this transport stage, bed-load transport rates remained relatively constant, being much lower (18 times) than those sampled for flows greater than the breakpoint. For instance, at the Ib-Cc vertical bed-load rates in phase I ranged from a minimum of <1 g $m^{-1} s^{-1}$ to a maximum of 13.4 g $m^{-1} s^{-1}$, with a mean value of 3.8 g $m^{-1} s^{-1}$. Once the breakpoint was exceeded, transport rates ranged from 2.6 g $m^{-1} s^{-1}$ to 189.4 g $m^{-1} s^{-1}$, with a mean value of 70.1 g $m^{-1} s^{-1}$. A similar pattern was observed at the Cc vertical. The bed-load transport rates in phase I ranged from a minimum of <1 g $m^{-1} s^{-1}$ to a maximum of 28.7 g $m^{-1} s^{-1}$, and the mean value was 8.5 g $m^{-1} s^{-1}$. In phase II, bed-load rates ranged from <1 g $m^{-1} s^{-1}$ to 625.0 g $m^{-1} s^{-1}$, with a mean value of 149.7 g $m^{-1} s^{-1}$.

Analysis of goodness-of-fit of the models indicated that in the Cc vertical the linear, power and piecewise functions were quite similar (Table 3), suggesting that all these models were comparable for estimating the mean rate of transport for a given discharge, but at the Ib-Cc sampling point the power function showed the highest SE compared to the other models (Table 3). In view of these results, the piecewise model was chosen for further examination since: i) it had the lowest SE; ii) this model allowed the identification of a threshold at which there was a substantial change in the rate of transport and, iii) when accompanied by grain-size data, the breakpoint analysis provided compelling evidence distinguishing between at least two phases of bed-load transport, as found by Ryan et al. (2002). In addition, the homoscedasticity and linearity of the residuals were also improved.

Bed-load texture with increasing flow strength

In the analysis performed above, it was found that there was a significant change in the behaviour of the sediment transport rates once a given flow had been achieved. We next investigated if there is also a shift in sediment texture associated with the change in bed-load transport rates. With this aim, the proportions of sand, granules, fine to medium pebbles, and coarse pebbles were plotted as a function of flow (Fig. 6), using the averaged bed-load grain-size distribution at 100 m^3 s^{-1} discharge increments. Results showed the existence of a shift in bed-load texture in the 950 m^3 s^{-1} discharge class, which corresponds to the transition from transport phase I to transport phase II. In phase I, bed-load grain-size distributions were unimodal in both verticals and the bed-load was dominated by gravel fractions (representing, respectively, 57% and 78% of the total load transported at the Ib-Cc and Cc sampling points). In this transport phase, the proportion of each individual class at the inner sampling point (Ib-Cc) did not change significantly (Table 4) while in the middle parts of the channel (Cc) there were minor but statistically significant deviations in grain-size distributions (Table 4). These could probably be related to chance variation in local sediment transport. In contrast, in transport phase II (i.e. $Q \geq 1250\ m^3\ s^{-1}$ discharge class), there was a substantial increase of sand sizes (reaching ~50%) at Ib-Cc, whilst pebble sizes and granules fell to values of 37% and 10%, respectively. Consequently, bed-load texture became bimodal at Ib-Cc but remained unimodal at Cc. This pattern can probably be related to the break-up of the armour layer, producing a sudden supply of fine material and its transfer to the inner parts of the cross section by secondary helical flows in the bend. At the Cc vertical the proportion of fine and medium pebble sizes tended to increase (from 59% to 75%), whilst sand fractions almost disappeared (representing ~2%). In addition, the proportion of coarse pebbles fell to a value of 15% and the per cent of granules decreased to a mean value of 13%. At this range of discharges, size distributions did not change significantly at either sampling point (Table 4), indicating that a near-constant grain-size distribution of bed-load was being transported.

Bed–load texture at-a-cross section

To better understand the dynamics described above, bed-load samples collected at the inner sampling point were paired with those gathered at the Cc vertical during the same traverse and day. For each of the paired samples, the ratio between the Ib-Cc and Cc data for the fractional transport rate of both fines (i.e. sand and granules; particle size ≤4 mm) and coarse fractions (i.e. pebble sizes; particle size ≥ 8 mm) was computed and then plotted against flow (Fig. 7). Accordingly, values below 1 indicated that fractional rates were lower at the Ib-Cc sampling point than at Cc. In contrast, values greater than 1 indicated higher fractional transport rates at Ib-Cc than at Cc.

The plot obtained showed that, below 900 $m^3 s^{-1}$ (phase I), any difference in the transport of fine and coarse fractions between the sampling points was obscured by the high degree of scatter. In this phase of transport, approximately 50% of values were greater than 1 (i.e. fines dominant) but 50% less than 1 (i.e. coarser dominant) indicating that there was non-dominance in the transport of fine or gravel sizes at a particular sampling point. In fact, these sizes tended to be equally mobilized across the river section. However, above 900 $m^3 s^{-1}$ (phase II) it was evident that fine fractions were transported predominantly through the inner part of the cross section. There, fractional rates of sand and granules were 6.8 times higher than at the Cc vertical, at the same time that coarser fractions were mainly transported through the middle parts of the cross section (fractional transport rates of gravel were 4.8 times higher); this indicates transference of fine fractions from the outer parts of the cross-section to the inner parts, probably because of the higher intensity of the secondary helical flows. Then, fine particles tended to be transported near the inner bank while coarse sizes were transferred throughout the middle parts of the channel.

Bed-load versus riverbed grain-size distributions

Differences between bed-load and riverbed texture for different discharges are illustrated graphically in Figure 8 (data for discharges less than 650 $m^3 s^{-1}$ are not shown). The plot reveals complex variation across the study section with increasing flow strength. At discharges below 650 $m^3 s^{-1}$, the bed-load trapped at each sampling point was, in general terms, largely finer than the bed surface and subsurface. Once this discharge was exceeded, bed-load initially coarsened and then tended to match the bed subsurface, the two being essentially indistinguishable as the breakpoint was approached (Fig. 8). In phase II, the bed-load turned out to be noticeably finer than the bed subsurface at the Ib-Cc vertical. In this phase of transport, variations in bedload texture at Ib-Cc were mostly related to fine fractions (e.g. < 11 mm), while bedload texture matched that of the bed subsurface almost perfectly for the upper part of the grain-size distribution (>11 mm). A similar pattern was observed in the central parts of the channel, in that bed-load tended to fine for flows up to 1500 $m^3 s^{-1}$; an absence of particle sizes < 8 mm was evident (Fig. 8).

The full significance of these trends was explored by examining the transport of bed-load size fractions relative to their abundance in the bed (Fig. 9). This allowed the evaluation of differences in transport intensity (e.g. Clayton & Pitlick, 2007). The degree to which the curves plotted in Fig. 9 deviate from the horizontal indicates how much the particle size distribution of the bed-load departs from that of the bed material (Powell et al., 2001). Accordingly, a range of nearly constant values of the sediment transport ratio indicate that these fractions are transported in a similar proportion as in the subsurface bed layer, while a departure from flatness of the line up or down suggests, respectively, overrepresentation or underrepresentation of a size fraction. Multiplication by i_{bi} showed that in phase I the finest particles were, in general terms, underrepresented at Ib-Cc, while the coarsest fractions (e.g. 32 mm) tended to be overrepresented. Granules and pebbles (4 to 16 mm) exhibited nearly constant values of the sediment transport ratio indicating that these fractions were transported in a similar proportion as in the subsurface bed layer. In phase II, both the finest and coarsest particles were greatly overrepresented whereas granules and fine and medium pebble sizes were transported in a “similarity range”, suggesting that the fractional transport ratio was independent of the particle size. Similar behaviour of the scaled fractional transport rates was observed at the Cc vertical (Fig. 9). There, sand sizes were underrepresented in phase I while the fractional curves of granules and pebbles tended to be flat. In phase II, sand fractions were again underrepresented whilst granule and fine and medium pebbles were transported in a “similarity range”, suggesting that all these particle sizes were mobilized under equal conditions. However, coarser particles showed a slight tendency to decline, indicating a weak tendency to be in a partial mobility state.

Discussion

Identification and interpretation of the bed-load transport phases

In this study, we observed differential behaviour of bed-load transport rates at two verticals of a river cross-section located at the end of a bend, once a given discharge was surpassed. This discharge was identified as the breakpoint between two sediment transport phases (phase I and phase II) by applying a piecewise regression model, in the same way as Ryan & Porth (2007) or Ryan et al. (2002) applied the model in coarse-gravel mountain streams. Our results confirm the appropriateness of the method for objectively defining transport phases in curved channels.

Our results showed that in phase I bed-load rates were much lower and with less variance than those obtained in phase II. In phase I the fitted line had a significantly lower slope than in the segment representing phase II. The low slope for the regression line in phase I suggests that factors other than flow hydraulics (e.g. sediment supply) play an important role in sediment transport, while the rapid increase in bed-load transport rate in phase II might be explained mainly by disruption of the riverbed (break-up of the armour layer) and the mobilization of the subsurface material, as pointed out in previous studies dealing with straight channels (i.e. Habersack & Laronne, 2001). The breakpoint between these two transport phases was found to be near the bankfull discharge, as Emmett (1999) and Ryan & Emmett (2002) observed for straight reaches in several rivers of the USA.

We also observed that, associated with the change in bed-load rates, there was also a change in bed-load texture, confirming the initial hypothesis. Accordingly, in phase I bed-load texture across the study section was dominated by gravel fractions while the presence of sand varied considerably. Overall, there were no significant differences in bed-load texture between verticals in phase I. This could be a direct result of the movement of the sand and fine gravel over a stationary or semi-stable bed surface deposited on the river channel during the waning stages of prior floods. In this transport stage, the bed-load was initially finer than the bed surface and subsurface, and the influence of secondary currents in transferring sediment laterally seems to have been minimal. However, as the flow discharge increased towards the breakpoint the bed-load tended more and more to match the bed subsurface, suggesting the progressive breakup of the surface layer of the riverbed and the initiation of transport of grains that had hitherto remained “hidden” in the bed subsurface. At this transport stage there was a clear link between the bed-load and the source and so almost the full range of particle sizes in the bed tended to be transported, i.e. the bed was fully mobilized.

Once the breakpoint had been exceeded, differential behaviour was observed across the study section. Sand fractions appeared greatly overrepresented in the inner parts of the river channel, but very underrepresented at the channel centre. This behaviour could be explained both because of the presence of secondary helical cells, which tend to transfer fine particles from the central part of the cross-channel to the inner bank (where a point bar is formed), and because of the entrainment of subsurface particles. In consequence, at the Ib-Cc (inner bank) site bed-load texture showed a trend towards bimodality whereas it was gravel-dominated in the central parts of the river channel. These results agree with those obtained by Clayton & Pitlick (2007) and Clayton

(2010), who showed that bed-load along a river bend clearly shifted from predominantly sand and fine gravel in the inner region to predominantly coarse gravel in the outer region. In a similar way, Church & Hassan (2002) and Wathen et al. (1995), in studies conducted in straight river sections, found that as the discharge increased, the texture of the mobile sediment changed and the particle distribution became more bimodal. The most symmetrical bimodal distributions were found during events with peak stress in the near-bankfull range. Our results show a trend toward bimodality at discharges close to or greater than bankfull, but this was observed only in the inner region of the river bend. In contrast, in the central parts of the river channel, bed-load particle distributions remained unimodal and dominated by gravel sizes . Therefore, a differential sediment transport behaviour across the riverbed appears at discharges around bankfull.

Relevance and limitations of the obtained results

The observation of this differential behaviour of sediment transport in a channel bend is highly relevant for, among others, the design of hydraulic infrastructures, the elaboration of geomorphological restoration works, or the computation of bed-load transport for river management and sediment yield assessment. For instance, the location of the sampling point during flood events plays an important role on the estimation of the total sand and gravel passing through the river bend. In the case of the Ebro, such estimates are important for determining the flux of sediment to the delta and hence the extent to which accretion is likely to keep pace with sea-level rise.

Flow in river bends is complex since secondary currents interact with the bed topography and variations in flow discharge can considerably alter the nature of such interactions. Therefore, the effect of this complex flow on lateral sediment fluxes, and hence on the stability of a river bend, is of particular interest for the study of the morphology of river meanders. Our results give evidence of strong lateral sediment sorting induced by the flow, providing a mechanism that is closely linked to the maintenance of the bend's morphology; coarse material is directed to the outer bank, where high shear stresses can mobilize the coarsest size fractions, while fine material is directed to the inner point bar, where shear stresses are lower and can mainly mobilize the fine fractions of the grain-size distribution. Such lateral trade-off would tend to mean that the coarse and fine size fractions supplied upstream would be transferred downstream the bend at a similar pace as they entered the reach, in spite of the large gradients of local bed shear stresses along and across the bend (Nuñez et al., 2017). We have argued that the most likely reason for the sudden abundance of fines near the inner bank in phase II is the break-up of the armour layer in upstream reaches. The inward routing of these fines would thus favour equalizing the mobility of fines and coarse size fractions in their transit along the bend. It must be noted, however, that processes in the bend we studied may differ to some extent from what occurs in natural river bends, for two reasons. First, the bend is confined by vertical walls, so that floods larger than bankfull cannot spill over into the flood plain, unlike in the unconfined reaches upstream and downstream of the study reach. Second, the inflection of the bend (in plan shape) in the region of the minimum radius of curvature is not gradual but contains an angularity that differs from bends in natural rivers, which closely approximate sine-waves (Langbein & Leopold, 1966). The effect of confinement will be to increase flow intensity for discharges larger than bankfull, which will enhance the gradient of bed-load transport rates as a function of water discharge in phase II (see Figure 3). In turn, the angularity of the bend may change the transverse components of the bottom shear-stress vectors, and with this alter the sediment lateral transfer and sorting. For instance, Smith & McLean (1984) showed that the outward bottom shear stress over the top of a point bar can be reduced as sinuosity increases. However, in spite of the likely effects on flow and sediment lateral transfer due to the confinement and shape of the reach, if changes in the transport intensity and texture respond to sediment supply gradients from upstream reaches, the two distinct phases described here should also be found in non-modified, regularly curved channels. However, further work must be done along an entire bend reach to clarify the effect of the interaction between flow hydraulics and bed topography in the definition of sediment transport phases. Particularly important would be to define if, in non-modified river bends at the breakpoint between phases, changes in bed-load texture coincide with a change in the gradient of the bed-load transport rates, as found in the Ebro section we studied.

Conclusions

In this study, we identified two well-differentiated phases (phase I and phase II) in bed-load transport, using samples obtained from two verticals in a cross section located at the end of a river bend in a gravel river, the Ebro at Tortosa, Catalonia. Both verticals, one placed at the centre of the river channel and the other one towards the inner part of the river bend, were opposite the point-bar of the bend.

Bed-load transport phases were established by means of piecewise regression models in the same way as in studies of straight reaches. The breakpoint between phases was found to be near the bankfull discharge, as observed in straight channels, when a rapid increment in the bed-load transport rate occurs with respect to water discharge. Thus, piecewise regression models can be successfully applied to river bend sections.

We also found that, associated with the change in bed-load transport rates between phases, there is a change in the texture of the sediment transported. Thus, at the inner part of the cross-section, bed-load texture in phase I is unimodal and dominated by gravel particles. Overall, no differences between the two studied verticals were found in this phase. However, in phase II a shift in bed-load texture was observed towards the inside of the river bend. In this region, bed-load texture changes from unimodal to bimodal due to a large increment of fine material (<2 mm). It is suggested that such increments of fines are related to both the break-up of the surface layer of the riverbed, which produces the sudden incorporation of the subsurface material, and the effect of the bend secondary flow; this, through interactions with the topography of the bottom, sweeps finer grains inward and coarse grains outward. In contrast, at the channel centre during phase II, bed-load remained unimodal and largely dominated by gravel fractions.

The study section is constrained by lateral walls and the layout of the curve in plan is not smooth, but shows an angularity in the region of minor curvature. These characteristics could have an important influence on the development of transport phases. Nevertheless, we consider that even in natural bends with a smooth shape, the same sediment transport phases are likely to occur, especially if the rupture of the coarse riverbed surface layer in upper sections is conditioning the characteristics of the material supplied to the bend. However, further research is needed to confirm this hypothesis.

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