Bed-material entrainment in a mountain river affected by hydropoeaking

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HIGHLIGHTS

• In the reach studied, hydropoeaking impacts mainly the furthest downstream section.
• Contrast in bed slope value and sediment supply regime control the impact intensity.
• Hydropoeaking causes the entrainment of the finer grains of the bed sediment.
• Tracer data for different flows showed a partially size-selective entrainment.
• Calibrated hiding-exposure formula allowed prediction of bed material entrainment.

GRAPHICAL ABSTRACT

ABSTRACT

Hydropoeaking, by artificially generated flow peaks, influences hydro-sedimentary dynamics on rivers and, consequently, affects bed material entrainment and transport. This study examines the onset of motion of sediment particles in four sections of a Pyrenean gravel-to-cobble bed river exposed to frequent hydropoeaking (once per day, on average). Five criteria of particle entrainment have been used to assess the prediction of the initiation of grain motion at-a-section scale. Theoretical entrainment conditions were validated using real observations of mobility by means of tracers. It was found that the maximum flow discharged by the hydropower plant mostly affects the furthest downstream section, located almost 17 km downstream, in which the finer fractions of the bed are entrained. The mobile grain sizes include up to coarse gravels (≈ 30 mm). Differences in sediment supply (imposed by tributaries), the value of the bed slope and the structure of the coarse surface layer decisively control the downstream variability of incipient particle motion between sections. Results from a 17 km study segment indicated that hydropoeaking generate partial transport, that is, a partially size-selective transport that occurs downstream from the hydropower plant and winnows the sand and small gravel further downstream, increasing armouring and depleting fine sediments.

1. Introduction

Hydropoeaking (hereafter HP) is presently perceived as a major sustainable alternative for renewable energy generation. However, this type of production typically affects the physical structure and process of the fluvial systems hosting HP stations. The generation of energy by means of turbines (whether they are associated to dams and weirs, or placed in run-of-the...
river production schemes, or both) causes sudden pulses, called hydropoeks, to river flow. These pulses are controlled by the demand for electric power. Hydropeaking alters the hydrological regime and flow hydraulics, hence habitat availability, therefore influencing the overall ecology of the river (see examples in Hauer et al., 2014; Schmutz et al., 2015; Vanzo et al., 2016; Smokorowski, 2022; and a complete review in Hayes et al., 2022). Sediment dynamics (river-bed structure, transport) are arguably among the processes affected by hydropeaking. Therefore, the need arises to keep analysing the effects of hydropoeks on multiple features of river processes, including sediment transport, with the aim of achieving the best possible coexistence between hydroelectricity generation and preservation of fluvial environments. The effect of hydropoeks on sedimentary processes, particularly bed-material entrainment, has not been extensively investigated (see some of the few examples in López et al., 2020 and Vericat et al., 2020). Scarcity of observational data is likely the main reason for this, and the absence of data and their transferability impede generalisation of results in comprehensive assessment of the impacts of hydropoeks on river behaviour.

Naturally, river bed particles are consecutively entrained, transported and deposited in river channels on the occasion of competent flow events (Church, 2006). The balance between the flow and weight destabilising forces (which tend to put particles into motion) and resisting or stabilizing forces (function of variables such as particle grain-size and density, angularity, hiding or protrusion of grains, and packing) determines the critical condition for incipient sediment motion (e.g. see Julien, 2002 and Garcia, 2008 for further details), which controls the frequency and magnitude of changes in channel geometry and form. Bed material transport in gravel bed streams commonly occurs at low rates. In this condition, the bed is only partially mobilised, a flow condition in which a portion of the grains on the bed surface are actively transported (Wilcock and McArdell, 1993), and much of the bed material, mainly the coarser, remains in place for extended periods of time (Hassan and Church, 2000).

River-bed sediments are commonly variable in both the vertical (in depth) and cross-sectional channel dimensions, as well as longitudinally (downstream). Vertically, the coarse surface layer is typically well sorted (i.e. greater selection of size classes, less scattered), while subsurface sediments typically show poorly sorted distribution, which leads to a wider grain size range (e.g. Parker and Klingeman, 1982; Vericat et al., 2006; Wilcock and DeTempe, 2005). The result is a coarse surface layer (i.e. armour) protecting subsurface sediments, which comprises the majority of the fractions present in the bed surface but also a substantial proportion of fine fractions (e.g. sand and fine gravel) not observed in the surface. This non-uniformity in grain sizes (sediment mixtures and depth variability) implies a greater conceptual and practical complexity to determining thresholds of sediment motion.

Mobility, furthermore, is conditioned by bed structure, which has a direct effect on particle hiding and protrusion (White and Day, 1982). This implies that, compared to uniform grain size beds, fine particles may require a higher threshold and coarser grains a lower one. Comparatively finer particles are protected by the larger ones, which protrude over the bed; under such grain-size and bed structural conditions, an increase of flow discharge (hereafter Q) does not necessarily imply a proportional increase in sediment mobility, hence, bed-material transport. The structure of sediment mixtures works to equalize the threshold shear stress required for the motion of all grains or equal-threshold scenario in opposition to the size-independence (hiding-free) limiting case where the initiation of transport of sediment mixtures would be highly selective based on grain size (Parker, 2008).

After reaching the mobility threshold, the bed begins to destabilize. Flows high above the threshold of sediment motion can unchain a larger destabilization, which, if it endures, may even cause changes in whole river morphology (e.g. effects on channel geometry and forms, and grain-size distribution). These dynamics also depend on the upstream supply of sediment, a process that is significantly affected in the presence of a dam. Streams with large sediment supply have finer textures, poorly developed surface structures and higher sediment transport rates (e.g., Lisle and Madej, 1992). When the sediment supply is low the development of a well-structured, coarse-textured bed significantly reduces the sediment transport rates (Dietrich et al., 1989; Church et al., 1998). It is important to characterise sediment motion thresholds, to understand the occurrence and the magnitude of events causing bed destabilization. In the particular case of hydropoeked rivers, such processes must be related to the competence, frequency and magnitude of such artificial flow pulses.

In addition, clogging of river bed surface by fines (silt, clay, fine sand) often carries collateral deleterious effects in hydropoeked rivers, especially in those affected by run-off-the river schemes, where by-passed river reaches are depleted from discharges capable to keep the transport of fines in suspension, thus favouring sedimentation. Fine sediment infiltration within the bed matrix has an impact on primary production, causing decreased variety and abundance of benthic macroinvertebrates (Wood and Armitage, 1997), also affecting salmonid reproduction (Coulombe-Pontriand and Lapointe, 2004); moreover the loss of porosity and permeability alter water exchanges between surface- and ground-waters (Brunke, 1999), and chemical interactions such as water temperature (Packman and Mackay, 2003).

River-bed sediments also vary spatially, in the cross-sectional channel dimensions and along river reaches and segments. Surface patches of fine sediment are also common in gravel-bed rivers. Patches are formed by accumulations of sand and gravel around particles of larger diameter, which provide a protective effect on the surrounding particles and favour sedimentation (e.g. Garcia et al., 1999). They occupy small proportions of river channels and the entrainment and transport of sediment from these structures hardly modify channel morphology (Vericat et al., 2008), but their mobilisation can be the cause of significant impacts on river ecological processes. For example, Gibbins et al. (2007) found that incipient bedload discharge from patches unchains involuntary macroinvertebrate drift in gravel-bed rivers.

Processes of partial bed mobility impelled by sediment mobilisation from patches are frequent in human-impacted river sites. This is the case in reaches exposed to hydropeaking in which flow discharge is artificially raised without a sediment supply from upstream. Fine grain fractions (i.e. sand, granules, fine and medium gravel), which are essential to a suite of river processes (e.g. fish spawning, invertebrate refuge), can be then entrained and depleted during competent events, unchaining for instance massive involuntary drift of fauna (also known as catastrophic drift i.e. disturbances such as floods physically dislodge animals) (e.g. Gibbins et al., 2007). The mobilisation of grains in these areas, even the mere particle agitation, can trigger such processes (Vericat et al., 2008; Batalla et al., 2010). Fine grains offer stimulating spots for agitations downstream from HP plants, where by-passed river schemes often carries collateral deleterious effects in hydropeaked rivers, especially in those affected by run-off-the river schemes, where by-passed river reaches are depleted from discharges capable to keep the transport of fines in suspension, thus favouring sedimentation. Fine sediment infiltration within the bed matrix has an impact on primary production, causing decreased variety and abundance of benthic macroinvertebrates (Wood and Armitage, 1997), also affecting salmonid reproduction (Coulombe-Pontriand and Lapointe, 2004); moreover the loss of porosity and permeability alter water exchanges between surface- and ground-waters (Brunke, 1999), and chemical interactions such as water temperature (Packman and Mackay, 2003).

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Cereghino et al., 2002), there is still a lack of studies examining their influence on river sedimentary dynamics and, in particular, on bed-material entrainment (see Aigner et al., 2017; López et al., 2020 and Vericat et al., 2020 as some few recent examples). From a broad perspective there are still numerous research questions that have not been fully addressed in the field of sediment transport in hydropeaked rivers such as (i) how does hydropeaking might affect bed armouring? (ii) what are the effects of hydropeaking on the removal and depletion of fines which are, in turn, essential for a variety of river biophysical processes? and (iii) what are the downstream effects of mobilisation of deposited sediment in hydropeaked rivers? All these questions have in common the need to examine the onset of particles from the bed. Within this context, the objective of this work is to further address these fundamental questions by analysing the changes on the entrainment of bed particles in a segment of a Central Pyrenean river subjected to a hydropeaking. Theoretical approaches (i.e. formulae, hydraulic estimations, entrainment predictions, see Section 3.6 for more details) were contrasted with particle tracer data, obtained in several sections regularly exposed to such flow pulses, in order to investigate downstream changes of threshold of sediment motion.

2. Study area

The study was carried out in the River Ésera (Central Pyrenees, Fig. 1A), over a 17-km long river segment between the Campo dam and the village of Santaliestra and San Quílez (Fig. 1B). The catchment area at the outlet of the study reach is 733 km². The basin has an elongated shape and the length of the main channel is around 75 km. Altitude varies between 3400 m and 540 m asl, with 85 % of the catchment located at altitudes higher than 1000 m asl. More than 70 % of the area has slopes between 30 % and 100 %, and almost 10 % of the area has slopes above 100 %. Catchment relief makes this basin a poorly populated region. Almost 53 % of its surface is occupied by herbaceous stratum vegetation or is without vegetation cover (bare soils), while the remaining 41 % is covered by forests, and 6 % is used for agricultural purposes.

The mean annual runoff registered at the gauging station of Campo (operated by the Ebro Water Authorities SAIH-CHE, code A-258, Fig. 1) for the period 1994–2016 is 517 hm³ (i.e. 1 hm³ = 10⁶ m³), yielding a mean annual discharge of 16 m³ s⁻¹. Mean annual maximum instantaneous discharge (i.e. annual flood) reaches 200 m³ s⁻¹, while less frequent floods (e.g. 10-year return period) can attain 470 m³ s⁻¹. The River Ésera is subjected to several impacts related to changes in land use (mostly natural afforestation), damming, and hydropeaking. The water flow at the inlet of the study segment is regulated by a network of seven hydropower plants that became operational in the first half of the 20th century. The cumulative capacity of the production units is 177 MW. The Eriste and Sesué HP plants (both located upstream of the study reach) have reservoirs with a capacity of 3.15 hm³ and 2.17 hm³, respectively, providing daily flow regulation (Galán, 2012). The rest of the downstream HP plants (Seira, Argoné, and Campo) operate with run-of-the-river schemes associated with weirs and small dams built in the river course and 35 km of galleries, which allow the water to be diverted to the production unit.

The maximum turbine discharge at the Campo HP plant (inlet of the study reach) is 20 m³ s⁻¹. On average, one hydropeak is generated per day, with a mean duration of 12 h and a mean discharge around 15.4 m³ s⁻¹ (Tena et al., 2022). Hydropeaking is also conditioned by the needs of recreational uses (e.g. rafting). The magnitude of the floods is little affected by the dam, due to their evacuation through the spillway and bottom outlet; however, the dam has a direct effect on trapping sediments; virtually all bedload is trapped while an important proportion of the suspended load is retained. This indicates that sediment supply at the inlet of the study segment is negligible and it is controlled by downstream sources such as direct hillslope erosion or tributaries. Hillslopes are composed by coarse formations like the alluvial terrace and conglomerates (44 %), mudstones, marl and sandstones (32 %) and limestones (15 %). The most important tributaries downstream are the rivers Rialbo,
Bacamorta and Foradada, composed of allochemical formations (limestone and dolomite: 50%), coarse loose formations (conglomerate, colluvium: 30%) and fine friable formations (mudstones marl and sandstone: 20%). Therefore, bed-material dynamics in the study segment will be directly influenced by bed structure (degree of armouring), in-channel sediment availability and the supply from the aforementioned sources or tributaries.

The bed is characterised as a gravel-to-cobble channel bed. The channel presents entrenched and meandering riffle-pool river reaches. The valley is highly confined due to topographical and geological context. Mapping of the valley bottom confinement using the GIS tool developed by O'Brien et al. (2019) indicates that 58.5% of the length is confined (lateral confinement of both banks) and 36.5% is confined to one side. Only 4.5% of the main channel is open (see confinement map in Fig. 1B for more details). The active width ranges between 18 m and 178 m, while the mean channel gradient is 0.7%. The average median bed surface material is 77 mm (see more information on the spatial variability of surface materials in Section 3.2). It should also be noted that there are patches of fine materials consisting of fine gravel, sand, clay and silt. The size of these structures varies through time, influenced by the supply of sediment from tributaries and hillslopes.

Four study sections, referred to as Campo Upstream, Campo Downstream, Pirámides and Santaliestra (from upstream to downstream, Fig. 1) have been selected. All study sections are situated downstream of the HP plant outlet. The first two sections are located between the Campo HP plant and the confluence with the main tributaries. The river bed presents an armouring ratio (i.e. the quotient between the surface and subsurface median particle size) of 2.05 in Campo Upstream; hence, the bed can be qualified as armoured. The armouring ratio in Campo Downstream is smaller (i.e. 1.50) than the one observed near the dam. In both sections the armour is broken-up during annual competent floods. Campo Upstream is the studied section with the largest armouring value. This attributed to the proximity to the dam and the negligible sediment supply form upstream. These two sections are contrasted in terms of confinement. The entrenched ratio (i.e. ratio of the valley width to the active width, as per Rosgen, 1994) is 1 for Campo Upstream and 2.4 for Campo Downstream. The Pirámides and Santaliestra sections are located downstream of the tributaries, and bed armouring ratio is 0.66 and 1.34, respectively (hence, not armoured). Pirámides has an entrenched ratio of 1 and a mean slope of 0.6%, while Santaliestra is steeper (geological control), with a slope of 1%, and wider, with an entrenched ratio equal to 2.0.

3. Material and methods

3.1. Channel topography

Channel topography was acquired by high-resolution topography, obtained by means of digital photogrammetry, specifically through Structure from Motion and Multi View Stereo Digital Photogrammetry (hereafter SfM) algorithms. Overall, SfM photogrammetry allow extracting high resolution orthophotomosaics and point clouds from a given number of images with overlapping scene (e.g. James and Robson, 2012; Westoby et al., 2012; Carrivick and Smith, 2019). A set of 1240 aerial photographs were taken from an autogiro at a flight altitude of approximately 350 m above the ground (Fig. 2A). An SLR Nikon D750 (28 mm Lens) camera was used.
Digital photographs were processed with Agisoft Photoscan Professional 1.2.2. In order to georeference, calibrate the cameras and get a correct scaling (i.e. registration), a total of 154 Ground Control Points (GCPs) were placed along 17 km of the river on both banks. Their GPS coordinates were recorded through an RTK-GNSS system (Leica Viva GS15) allowing 3D quality below 5 cm. Of the 154 GCPs, 77 were used to register the point cloud while the other 77 GCPs were used as check points to quantify the errors. The 2D horizontal error (root mean square error) was 0.056 m, while the vertical error was 0.13 m on dry areas and 0.25 m in the submerged areas. The point cloud in wet surfaces is affected by refraction of light at the water-air interface. After the correction of the refraction in the submerged areas, the vertical error decreased to 0.185 m. This correction is fully described below. An orthophotomosaic with a resolution of 0.1 m and a terrain point cloud with a mean density of 46 points m$^{-2}$ (Fig. 2A) were generated over an area of 14.2 km$^2$.

As indicated, the point cloud in wet surfaces is affected by refraction of light at the water-air interface. This effect causes an underestimation of the depths (e.g. Fig. 2B) because light rays passing through an air-water interface are shifted and depths, and thus elevation, are biased. To correct this bias, an empirical refractive correction model was applied to the data following the procedure of Woodget et al. (2015): $d = n_d \cdot d_w$, where the real depth ($d$) can be estimated by knowing the apparent water depth ($d_w$) and the refractive index or coefficient ($n_d$). A set of 644 check points was collected during the day before the flight (Fig. 2A); 286 of these in exposed sediments and 358 in the submerged channel perimter (from 0 to 1.3 m depth). Water flow on the day of the flight was the same as the day the check points were surveyed. Check points in the submerged zone allowed both to develop the empirical refractive model and to evaluate the general accuracy of the channel bathymetry. A set of 70 % of the submerged points was used to fit the empirical refractive correction model. The remaining 30 %, called the test data set, were used to evaluate the accuracy of the data once corrected. Each elevation value (m asl) of the submerged check points ($Z_{ChP}$) was transformed to water depth ($d$). In order to make this transformation, a model of the water surface elevation ($Z_{WSE}$) needed to be developed, as will be explained. The water depth of each point was obtained by subtracting the elevation of the submerged check points from the water surface elevation (i.e. $d = Z_{WSE} - Z_{ChP}$, see Fig. 2B for a graphical representation of this transformation).

To generate the water surface elevation (hereafter WSE) model, an uncorrected Digital Surface Model, computed from Agisoft Metashape Professional 1.6.5, and a uniform Manning's roughness coefficient of 0.025 m$^{-1/3}$ were used to run a series of flow simulations along the study segment, by means of the Iber 2D hydraulic model (see Section 3.4 for details in terms of modelling). This value of Manning’s coefficient ($n_h$) has been estimated for the category of cobble-bed rivers from table (Julien, 2002), graph (Ferguson, 2010) and the formula of Henderson (1966): $n_h = 0.038D_0^{0.6}$ ($D_0$ of the bed surface material in m). The value of flow discharge was modified until the water surface extension of the simulation fitted with the water surface extension observed in the orthomosaic. When this was achieved, the WSE model from this simulation was exported. The submerged check points were intersected with the WSE model in order to extract the elevation of the water surface in each point ($Z_{WSE}$). The difference between $Z_{WSE}$ and $Z_{ChP}$ provided the depth of each point, considered the real depth ($d$). Additionally, all elevation values in the wet channel obtained through SfM and ZSfM were also transformed to apparent water depth ($d_w$), following the same procedure. A statistical relationship between $d$ and $d_w$ was obtained (grey points in Fig. 2C). Then, a correction coefficient was calibrated to minimize the differences between the apparent depth and what was considered the real depth. From a cross-validation calculation (jackknife), an optimum coefficient was obtained, which yielded the refraction correction model. Evaluation of the quality of the refraction correction model was performed on a validation set consisting of 99 points (Fig. 2D). The average error was reduced from $-0.200$ m to $-0.020$ m and the root mean square error from 0.250 m to 0.185 m.

Before to correct water refraction the point cloud was filtered in order to remove all errors caused by water turbulence and shadows. Points in shaded zones and those located in turbulent areas were removed by means of a classification of the aerial image obtained through the digital photogrammetry process. Apparent water depth points for the whole wet channel were subsequently corrected, applying the equation shown in Fig. 2C. After, the corrected depth points (m) were transformed to elevations (m asl), i.e. the corrected depths were subtracted from the water surface elaboration model ($Z_{corrected} = Z_{WSE} - d_{corrected}$). These corrected wet points were combined with the point cloud for the dry points to generate a hybrid DEM as follows. The entire corrected dense point cloud was regularized by means of the ToPCAT algorithm (Brasington et al., 2012; Ryckov et al., 2012). ToPCAT is freely available from the Geomorphic Change Detection software as an ArcMap tool, see http://gcd.riv erscapes.xyz/ and Wheaton et al. (2010) for details of the methodological developments. The minimum elevations within a 0.5 × 0.5 m grid cell were extracted and were considered to represent the ground elevation of each grid. Vegetation was filtered out through the orthomosaic and, lastly, triangulated irregular networks were calculated from the filtered minimum observations, from which a 0.5 m resolution hybrid DEM was computed, providing a continuous model of the ground along the 17-km long segment.

3.2. Bed material characterisation

The grain-size characterisation of the bed surface sediment was carried out through the pebble-count method (Wolman, 1954). Bed-surface particles were collected along transects at each section. This method is indicated for gravel and cobble-bed streams, as it is difficult to pick up particles smaller than 8 mm. Grain-size samples were collected during a field campaign in September 2018. Bed-surface particles were sampled in morphological equivalent units. Between 120 and 200 particles were measured at each of the four studied sections, and grain-size distributions (hereafter GSD) were truncated, considering only material ≥ 8 mm (Fig. 3).

3.3. Field assessment of particle mobility

Particle mobility was assessed during autumn 2018 in the four study sections using two different tracer techniques: (i) lines of individual painted particles, and (ii) painted pebble squares. It should be noted that, in this work, the field assessment of particle mobility was intended to contrast the tracer data with the predictions of the selected criteria for estimating the sediment motion threshold, a way to validate the theoretical approach selected (see Section 3.6 for more details on these selected criteria). Consequently, a complete analysis of bed mobility is out of the scope of this research. Tracers have been widely used to study bed mobility in fluvial...
3.4. Hydraulic modelling

Flow hydraulics associated with targeted Q were simulated along the whole river segment using the Iber 2D hydraulic model (Bladé et al., 2014). A regular mesh of 1.25 m was generated by importing the 0.5 × 0.5 m DEM resolution (see Section 3.1). The size of the mesh was established by optimising the computational time and providing acceptable results at a section scale, the scale in which entrainment is analysed (see Section 3.5). Although finer meshes may have a direct impact on maximum and minimum values of hydraulic variables through a given reach, preliminary sensitivity analyses in the study site indicated that these differences are not significant at the cross-sectional scale. Surface roughness was parameterised as spatially uniform with a Manning’s roughness coefficient value of 0.025 m s⁻¹/³ (see Section 3.1). The model was run at steady flow for each target Q. Targeted Q were 2, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 150, 200, 225, 250, 300, 355, 400, 477, and 600 m³ s⁻¹ (see a visual representation of several of the simulations in Fig. 4).

The assessment of model performance was made using spatially distributed surveys from an acoustic Doppler current profiler (SonTek RiverSurveyor M9) coupled to an RTK-GNSS system. Water depth, water surface elevation and mean flow velocity was surveyed at different Q (2, 5, 8, 17, and 20 m³ s⁻¹) in Campo Upstream, Campo Downstream and Santaliestra (providing >4600 real observations). The Mean Absolute Error (MAE) between observed and modelled data was computed as:

\[ \text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |x_{\text{obs}} - x_{\text{mod}}| \]  

in which \( x_{\text{obs}} \) = observed \( i \) value of the variable; \( x_{\text{mod}} \) = modelled \( i \) value of the variable; \( n \) = number of data; and \( x \) represented independently the following three variables: (i) mean flow velocity (m s⁻¹); (ii) water depth (m); and (iii) water surface elevation (m asl). Therefore, three MAE were calculated for each Q. The MAE of flow velocity ranged between

![Flow hydraulics associated with targeted Q were simulated along the whole river segment using the Iber 2D hydraulic model.](image)

**Fig. 4.** Example of the results of the hydraulic models developed in this study. On the left side is an example of the painted line and square tracer used for field assessment of particle mobility. Where aDcp is the acoustic Doppler current profiler.
0.12 m s\(^{-1}\) and 0.20 m s\(^{-1}\) (with an average value in terms of relative error of 32 %) for low flows (i.e. 2, 5 m\(^{3}\) s\(^{-1}\) and 8 m\(^{3}\) s\(^{-1}\)), and between 0.14 m s\(^{-1}\) and 0.22 m s\(^{-1}\) (mean value of the relative error of 30 %) for medium Q (i.e. 17 m\(^{3}\) s\(^{-1}\) and 20 m\(^{3}\) s\(^{-1}\)). The MAE for water depth oscillated between 0.13 m and 0.21 m (mean relative error of 25 %) for low Q and between 0.15 m and 0.24 m (mean relative error of 15 %) for medium Q. The water surface elevation MAE for low and medium flow are between 0.13 and 0.14 m asl and 0.13 and 0.16 m asl, respectively (note that in this case, the values in terms of relative error are very low since water surface elevation is >500 m asl).

3.5. Estimation of shear stress

By considering the equilibrium of forces on a control volume for one-dimensional steadily gradually varied flow in a wide open channel (i.e. \(R \sim y\)), the mean boundary shear stress in a cross-section \(\tau\) can be estimated as:

\[
\tau = \rho g y S_f
\]  
(2)

in which \(\rho = \text{density of water; } g = \text{acceleration due to gravity; } y = \text{mean water depth; } R = \text{hydraulic radius; and } S_f = \text{friction slope or energy gradient.}

However, the Iber model allowed us to estimate the shear stress distribution on the channel boundary for two-dimensional flow throughout the whole river reach for any of the modelled \(Q\) (i.e. the same list as that specified in Section 3.4). Nevertheless, it should be pointed out that, in this work, sediment entrainment was predicted at-a-section scale (i.e. one-dimensional) for each of the four studied sections. A transect was determined for each section, about perpendicular to the main channel direction. It should be remembered that these transects are not, strictly speaking, cross sections to the flow, since the flow simulation is not one-dimensional. Iber supplies the value of the integral of shear stress distribution on the channel boundary in these transects for each of the modelled \(Q\). The mean shear stress exerted by the flow in each section and for any \(Q\) was determined by dividing that integral value by the wetted perimeter. Hence, a set of 21 points (corresponding to the same number of targeted flows) with values \((Q, \tau)\) was obtained for each section, and a simple power law regression was applied to these points:

\[
\tau = aQ^b
\]  
(3)

in which \(\tau = \text{mean boundary shear stress; } Q = \text{flow discharge; } a = \text{coefficient; and } b = \text{exponent.}\) A power law function was adopted because, given a section, the mean depth \((y)\) and flow discharge \((Q)\) can be correlated by a simple power law, according to the at-a-station hydraulic geometry concept (Leopold and Maddock, 1953; Dingman and Afshari, 2018) and due to the relationship between the mean boundary shear stress \((\tau)\) and the mean water depth \((y)\) (i.e. Eq. (2)).

3.6. Prediction of particle entrainment

The resistance of a sediment particle to be entrained was assessed by the dimensionless critical shear stress \((\theta)\), or the critical value of the Shields number) needed to set in motion a particle of size \(D_i\) and was estimated as:

\[
\theta_{ci} = \frac{\tau_{ci}}{g(\rho_i - \rho)D_i}
\]  
(4)

in which \(D_i = \text{size of particle median axis for which } i \% \text{ of the particles are finer; } \tau_{ci} = \text{critical shear stress for } D_i; \text{ and } \rho_i = \text{sediment density. Due to the relatively low value of the mean bed slope in the studied reach (Section 2.2), the analytical correction that takes into account the effect of high slopes on the Shields number (e.g. Armanini, 2018) has not been applied.}

The condition for incipient motion of sediment (i.e. threshold of motion) was determined by establishing equality between critical shear stress of a particle of size \(D_i (\tau_{ci})\) and the mean boundary shear stress of the cross section \((\tau)\). So, to unify the notation and avoid confusion, Eq. (3) is expressed as:

\[
\tau = aQ^b
\]  
(5)

in which \(\tau = \text{critical mean boundary shear stress for } D_i; \text{ and } Q = \text{critical discharge for } D_i; a = \text{coefficient; and } b = \text{exponent.}

In coarse river beds of poorly sorted size distribution, the so-called hiding-exposure effect was observed, i.e. the process in which small particles are hidden from the flow by larger and more exposed particles (e.g. Garcia, 2008; Bathurst, 2013). This effect makes the prediction of the beginning of the particle’s motion more difficult. The hiding-exposure effect over the dimensionless critical shear stress can be estimated as:

\[
\theta_{ci} = \theta_{ci}^{0.51 - 0.77}Q^{-0.057}
\]  
(6)

in which subscript \(r\) refers to the reference particle size that is not influenced by the hiding-exposure effect. In this work it has been assumed, as usually, that this reference particle size corresponds to \(D_{50}\) of the bed surface material. The exponent \(a\) or hiding factor represents the dependence of the dimensionless critical shear stress on relative particle size. If the hiding factor is zero \((a = 0)\), this means that the relative size effects are not decisive, and critical shear stress is a function of absolute grain size (constant critical value of the Shields number). On the contrary, if \(a = -1\), equal mobility is assumed (i.e. grains of different sizes begin their motion at the equal mean shear stress).

Five different criteria were used to estimate the values of the coefficient and exponent of Eq. (6). First, the Miller et al. (1977) and Yalin and Karahan (1979) criterion was used (hereafter designated M-Y&K) as representative of purely size-selective entrainment (i.e. \(a = 0\) ) (Eq. (7) in Table 1). This equation was determined by the mentioned authors for hydraulically rough turbulent flow from a selection of databases acquired in flumes with beds of non-cohesive particles. The second criterion was proposed by Komar (1987) and was validated with >150 measurements in different fluvial and marine environments (with particle sizes varying between very fine gravel to boulders and \(D_i/D_{50}\) between 0.3 and 30). The proposed empirical equation (Eq. (8) in Table 1) has a hiding factor \((a)\) of \(-0.6\) (i.e. between 0 and \(-1\)) and implies a medium dependence of critical shear stress on particle size; it can be classified as partially size-selective entrainment. The third criterion was the equation fitted by Dey

<table>
<thead>
<tr>
<th>Reference</th>
<th>Equation</th>
<th>(\theta_{ci} (-))</th>
<th>(a (-))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller et al. (1977); Yalin and Karahan (1979)</td>
<td>7</td>
<td>0.045</td>
<td>0</td>
</tr>
<tr>
<td>Komar (1987)</td>
<td>8</td>
<td>0.045</td>
<td>-0.60</td>
</tr>
<tr>
<td>Dey and Ali (2019)</td>
<td>9</td>
<td>0.057</td>
<td>-0.76</td>
</tr>
<tr>
<td>Wilcock and Crowe (2003)*</td>
<td>10</td>
<td>0.036</td>
<td>-1 + \frac{0.57}{\log(D_i/D_{50})}</td>
</tr>
<tr>
<td>This study (data compiled rivers worldwide)</td>
<td>12</td>
<td>0.045</td>
<td>-0.77</td>
</tr>
<tr>
<td>This study (River Ésera tracer data)</td>
<td>13</td>
<td>0.018</td>
<td>-0.54</td>
</tr>
</tbody>
</table>

* As presented in McCarron et al. (2019).

b In this equation the value of \(\theta_{50}\) is a function of the proportion of sand in the surface layer GSD. In this study it was assumed to be zero.
and Ali (2019) to a large database (about 500 data, with $D_i/D_{50}$ varying between 0.03 and 20), compiled with both field and flume data from several sources (Eq. (9) in Table 1). The fourth criterion was obtained by fitting Eq. (6) to an extensive database compiled specifically for this study from publications by various researchers. Data obtained in the field (gravel or coarse bed material rivers) and agreeing with the flow competence method (largest particle mobilised) were selected. See results and more detailed information on the selected database and the fitted equation in Section 4.2 and Fig. 5. Lastly, a fifth criterion was adopted in which it is assumed that the hiding and exposure effects are different and that, therefore, the $a$ value in Eq. (6) is variable with the $D_i/D_{50}$ ratio. Specifically, the equation of Wilcock and Crowe (2003) was adopted, which was proposed from the application of the reference method to flume data (Eq. (10) in Table 1). However, it should be noted that results of the reference and flow competence methods are different (Buffington and Montgomery, 1997), as it was observed in studies in which both have been applied to the same sites (e.g. Ashworth et al., 1992; Wathen et al., 1995; Batalla and Martín-Vide, 2001). Indeed, expressed in absolute value, the exponent $a$ of Eq. (6) is between 15% and 35% higher using the reference method.

To choose a single equation of bed entrainment (i.e. the equation that best represents the conditions of the study segment), prediction of the five equations or criteria mentioned above was contrasted with the values ($D_i/D_{50}$, $\theta_{ci}$) obtained from the tracer data available for the four sections studied (Section 3.3). The equation (or criterion) of bed entrainment finally chosen was the best fit on the tracer data. Therefore, this equation was subsequently used as the only criterion for predicting downstream changes at the onset of sediment motion.

Finally, a simplified equation for the calculation of bed entrainment was obtained by combining Eq. (4), Eq. (5) and Eq. (6) taking $g = 9.81$ m s$^{-2}$, $\rho_s = 2650$ kg m$^{-3}$ and $\rho = 1000$ kg m$^{-3}$ and considering the dimensionless critical stress ($\theta_{ci}$) equation chosen. The resulting equation is a simple power law (see Supplementary material A):

$$Q_{di} = cD_i^d$$ *(11)*

in which $Q_{di}$ = critical discharge needed to set in motion a particle of size $D_i$; $D_i$ = size of particle median axis for which $i$% of the particles are smaller; $c$ = coefficient; and $d$ = exponent.

### 4. Results and discussion

#### 4.1. Mean boundary shear stress

Table 2 shows the power law regression between $Q$ and mean boundary shear stress ($\tau$) for each section, as well as the value of the coefficient of determination for each regression ($R^2$) (third and fourth columns, respectively). For the four sections, the goodness-of-fit of the power law regression can be considered acceptable ($R^2$ varies between 0.96 and 0.98) and statistically significant (in all cases $p$-value < 0.0001). The regression equation corresponding to Pirámides section diverges the most from the rest. This is due to the fact that for, lower flows, the mean shear stress predicted in this section is comparatively lower than for the rest of the sections and, in contrast, the shear stress for the four sections tend to converge for the highest flows.

#### 4.2. Dimensionless critical shear stress

Fig. 5 shows the relationship between dimensionless critical shear stress ($\theta_{ci}$) and relative particle size ($D_i/D_{50}$), both for the measured entrainment using traced particles and for the five criteria adopted to estimate the values of the coefficient and exponent of Eq. (6), as explained in detail in Section 3.6. Measured entrainment in River Ésera, composed by six observations (Fig. 5), was determined by the flow competence method; that is, matching the diameter (b-axis) of the coarsest particle mobilised with the maximum discharge occurring between periods the tracers were recovered (see Section 3.3). The 15th October 2018 flood was the only episode in which tracer mobilisation was observed in all four study sections. In terms of
mobilisation during hydropoeaking, the only detected bed disturbance after the hydropoeak on 19th October 2018 was a patch of fine gravel deposited on one of the painted squares in the Campo Downstream section. The largest particle of this patch was measured. In the case of the hydropoeak on 20th September 2018, only the mobilisation of a tracer particle from a painted square in the Santaliestra section was observed. A regression is fitted based on these six points (i.e. River Ésera data regression). For comparison purposes, the five entrainment observations from the neighbouring River Cinca presented in López et al. (2020) have also been represented. Finally, the curves corresponding to the M-Y & K, Komar (1987), Wilcock and Crowe (2003) and Dey and Ali (2019) equations and the mobility observations together with the regression equation corresponding to the field database compiled in this study have also been represented.

The database is composed of a total of 491 entrainment observations, taken from 15 bibliographic references (see Supplementary material B) and from 22 unpublished data obtained after a reassessment of bedload measurements in the rivers Tordera (Garcia, 1999) and Ebro (López et al., 2014). The $D_{50}$ is the maximum grain size transported between 0.014 and 5.3. Despite the scatter in the cloud associated with the compiled database (for a given value of $D_{50}/D_{50}$, the dimensionless critical shear stress ($\theta_c$) varies over a broad range), a general trend of decreasing $\theta_c$ value with increasing $D_{50}/D_{50}$ is clearly evident in Fig. 5. The regression equation fitted to that database according to Eq. (6) is Eq. (12) showed in Table 1.

The value of the coefficient of Eq. (12) ($\theta_{50} = 0.045$) coincides with that of Eq. (8), by Komar (1987), and the exponent ($\alpha = -0.77$) is very similar to Eq. (9), from Dey and Ali (2019). Fig. 5 shows that the predictions are quite similar over the $D_{50}/D_{50}$ range covered by these three equations, Eqs. (8), (9) and (12). However, in comparison, the points of the tracer particles associated with the River Ésera describe a trajectory with much lower values of the dimensionless critical shear stress. The same can be said about Eq. (10), even though it sets a variable $\alpha$ value. In fact, with the exception of one of the points (belonging to the Santaliestra section), the data align practically with the lower envelope of the compiled database. That is, Eqs. (8)–(10) and (12) predict a threshold of sediment motion clearly higher than that measured by the tracer particles in the River Ésera. These equations predict that the mean boundary shear stress required to mobilise a particle of diameter $D_i$ is much higher than that estimated from the tracer particles. In contrast, the position of the points defined by the tracer particles of the River Cinca fitted much better to the curves of the previous equations plotted, especially Eq. (8). Entrainment measurements also show that the River Ésera does not have purely size-selective entrainment conditions, represented by Eq. (7). Therefore, Eqs. (7)–(10) and (12) are not suited to predict the threshold of sediment motion in the four sections studied in the River Ésera. As an alternative, the regression equation fitted to the tracer particle data from the River Ésera was adopted. The fitted equation is Eq. (13) ($R^2 = 0.83, p = 0.012$) showed in Table 1 and also represented in Fig. 5. As can be seen in Fig. 5, the plot of Eq. (13) practically coincides with the lower envelope of the point cloud belonging to the compiled database. This is due to the low value of the coefficient ($\theta_{50} = 0.018$). The value of exponent (hiding factor $\alpha = -0.54$), indicating a medium dependence of critical shear stress on particle size, is similar to that obtained by Whitaker and Potts (2007) ($\alpha = -0.59$), based on regression analysis of flow competence data (bedload samples) in a gravel-bed stream.

Finally, the equation used to estimate the threshold of sediment motion in the four sections of the River Ésera was the version of Eq. (11) obtained by combining Eqs. (4), (5) and (13). This equation for each of the four study sections is presented in the last column of Table 2 (in which the value of $D_{50}$ has already been substituted for each section).

4.3. Downstream changes on the onset of sediment entrainment

Fig. 6 shows the equations of threshold of sediment motion for the four study sections, presented in the last column of Table 2. It is important to note that these equations have been plotted in the $D_i$ interval between $D_{50}$ and $D_{50}$ of the grain size distribution of each section (Fig. 3). This is why the four curves cover a range of representation that, in absolute terms, is different for each one (the limits of the curves depend on the particular GSD of each section). Therefore, the four curves share only the particle size range between 0.04 m and 0.1 m. The value of the exponent of the four equations (Table 2) varies in a relatively narrow range (between 0.5 and 0.7), so the slope of the corresponding curves shown in Fig. 6 is similar. The major difference among these four equations is due to the value of the coefficient, $c$ in Eq. (11), which varies between 144 and 389 (Table 2).

For comparison purposes, the equations of the first two upstream sections (i.e. Campo Upstream and Downstream) can be considered as a single set, given the similarity of their curves (Fig. 6). In this group, when setting the value of $D_i$, the predicted $Q_e$ value is comparatively high (more flow is required to entrain a $D_i$ compared to downstream sections). That is, it shows a higher threshold of sediment motion than the rest of the two downstream sections (i.e. Pirámides and Santaliestra). This is mainly explained by the fact that the bed surface layer in the two Campo sections is coarser (even armoured in the uppermost section) than in the two downstream sections, for most of the GSD range (see Fig. 3). In contrast, in the case of the Santaliestra equation (the furthestmost section), when setting the value of $D_i$, the predicted $Q_e$ value is comparatively low (less flow is required to entrain a $D_i$ compared to all other upstream sections). That is, it shows a lower threshold of sediment motion than the rest of the sections (see Fig. 6). The main reason for this is that, given a flow rate $Q$, the value of the mean boundary shear stress predicted by the equation fitted to the Santaliestra section is comparatively higher than the rest of the upstream sections (see third column of Table 2). This is because the value of the mean longitudinal bed slope in the Santaliestra section is almost double the bed slope of the rest of the upstream sections. Finally, the plot of the equation associated with the Pirámides section is located below the trajectory of the equations of the Campo sections and above the curve of the Santaliestra section (although closer to the plot of the curves of the Campo sections). The size of the bed surface material in the Pirámides section is significantly smaller than in the other sections. This could have caused the threshold of sediment motion predicted for the Pirámides section to be comparatively lower than for the other sections. However, as seen above, its critical flow rate curve of incipient sediment motion occupies a relatively high position (Fig. 6). This is because the value of the mean shear stress predicted in the Pirámides section (Table 2) is significantly lower than the corresponding value in the other sections for discharge below 100 m$^3$s$^{-1}$.

For the purpose of comparing the four curves, the prediction of $Q_e$ can be contrasted by setting the same value of $D_i$ for all sections. In this
case \(D_i = 77\) mm (small cobble), which is the median value of \(D_{95}\) in the four sections. Accordingly, for the Campo sections curves, to initiate the movement of a 77 mm diameter particle, a mean \(Q_c\) value of 71 m\(^3\) s\(^{-1}\) would be required. However, a \(Q_c\) of only 32 m\(^3\) s\(^{-1}\), is required in the Santaliestra section. Finally, for a \(D_i = 77\) mm, the Pirámides section entrainment equation predicts a value of \(Q_c\) of 55 m\(^3\) s\(^{-1}\).

### 4.4. Bed-material entrainment during floods and hydropeaking

We have assumed two well-differentiated sediment entrainment conditions during floods, driven by the distinct coarsening of the river bed; a lower limit based on the critical shear stress for \(D_{94}\) particle size and an upper limit for a shear stress equivalent to two times the critical shear stress of the \(D_{95}\). These limits were considered to predict phase 2 of bedload transport in armoured beds (Recking, 2010) and to establish the dynamically stable phase in a conceptual model of channel stability in gravel-bed rivers (MacKenzie et al., 2018).

For the Santaliestra curve (Fig. 6), the lower \((D_{94} = 151\) mm) and upper limits are predicted under a \(Q_c\) of 48 m\(^3\) s\(^{-1}\) and 115 m\(^3\) s\(^{-1}\), respectively. Both values are lower than the peak \(Q_c\) associated with annual floods. It should be recalled that the Santaliestra section shows a more mobile bed, i.e. less flow required to entrain a given \(D_i\). For the Campo sections, with a comparatively more stable bed, lower limit \((D_{94} = 216\) mm for Campo Upstream and 140 mm for Campo Downstream) is predicted under an average \(Q_c\) of 118 m\(^3\) s\(^{-1}\) (varying between 107 m\(^3\) s\(^{-1}\) and 128 m\(^3\) s\(^{-1}\)). These values are also lower than the peak \(Q_c\) associated with annual floods. The upper limit is predicted under an average \(Q_c\) of 302 m\(^3\) s\(^{-1}\) (varying from 288 m\(^3\) s\(^{-1}\) to 316 m\(^3\) s\(^{-1}\)), a condition reached during floods with a recurrence interval between four and five years. Finally, lower \((D_{94} = 68\) mm) and upper limits in the Pirámides section requires only \(Q_c\) values of 52 m\(^3\) s\(^{-1}\) and 108 m\(^3\) s\(^{-1}\), respectively. Both values are lower than the peak \(Q_c\) associated with annual floods and similar to those predicted for the Santaliestra section. This is mainly due to the low value of \(D_{94}\) for the Pirámides section.

Summarising, with regard to entrainment conditions of coarser bed material during floods, results indicate that the studied reach of the River Ésera has a frequently mobilised bed. However, in relative terms, a downstream change in mobility has been detected, i.e. from a more stable bed where mobility is less frequent in sections close to the hydropower station to a more mobile and frequently mobilised bed in the further downstream sections.

Hydropreaches a maximum \(Q_c\) of 20 m\(^3\) s\(^{-1}\). So, in this study, this value is adopted as the maximum entrainment capacity caused by hydropreaches for the entire river segment. In an initial analysis, base flows and reduced peak flow due to downstream routing of the hydrograph were ignored. Fig. 6 shows hydropreaching \(Q_c\) as a parallel line to the x-axis. The intersection point of this line with the particle entrainment curves determines the maximum grain size for the incipient motion \((D_i)\) at each study section associated with the maximum hydropreaching \(Q_c\), i.e. when \(Q_{cr} = 20\) m\(^3\) s\(^{-1}\).

Fig. 6 shows that the only intersection of the horizontal line \((Q_{cr} = 20\) m\(^3\) s\(^{-1}\)) occurs in the Santaliestra section, the most downstream section. In this case, the initiation of motion is predicted for a sediment particle size less than or equal to 34 mm (approximately equivalent to \(D_{10}\) of the bed surface in this section, Fig. 3). Since the Santaliestra section is the furthest from the outlet of the Campo hydropower plant (Fig. 1), it is of interest to assess the attenuation effect of maximum \(Q_c\) of the hydropreaches in this section due to the propagation of the hydrograph (e.g. Hauer et al., 2013). From the analysis of recorded hydropreaches at the study reach and the simulation of typical hydropreaches (2D modelling at unsteady-flow conditions using Iber), it has been concluded that the attenuation effect is very moderate; it has been estimated that the maximum value of the hydropreach at Santaliestra decreases to 18 m\(^3\) s\(^{-1}\). In this case, the threshold of motion is predicted for a grain size less than or equal to 28 mm (approximately equivalent to \(D_{10}\) of the bed surface in this section, Fig. 3). Therefore, results indicate that the entrainment of sediment in the Santaliestra section caused by hydropreaches would only affect the smaller fractions of the surface GSD (Fig. 3).

For the remaining sections located upstream (Campo Upstream and Downstream and Pirámides), peak flows associated with hydropreaching \((Q_{cr} = 20\) m\(^3\) s\(^{-1}\)) are not able to entrain a significant \(D_i\) of the surface GSD. It is worth remembering that in Fig. 6, \(D_i\) was represented only in the interval between \(D_{95}\) and \(D_{94}\) of the surface GSD of each section. According to the power laws (last column of Table 2) of these sections, the maximum particle size corresponding to the threshold of sediment motion for a discharge of 20 m\(^3\) s\(^{-1}\) would be about 10 mm (medium gravel) for all three sections; the size is close to the lower limit of detection in the method used to sample surface sediment (Section 3.2). Nevertheless, these are the size fractions that are prevalent in patches of fine materials in fluvial environments similar to the River Ésera (e.g. Garcia et al., 1999; Vericat et al., 2008, 2020) and would therefore entrain, if present. Within this context, in those sections where the presence of fine particles is considered significant, combining pebble-count and area by weight samples (Reherals and Bray, 1971) may provide a GSD representative of the full spectrum of sizes on the bed (e.g. Vericat et al., 2006). Combined surface grain size distributions can be generated according; for instance, Fripp and Diplas (1993) and Rice and Haschenburger (2004).

Generally, sediment transport induced by hydropreaching in the studied segment can be interpreted as phase I transport (e.g. Jackson and Beschta, 1982; Ryan et al., 2002) that involves the transport of fine grains over the coarser particles constituting the bed. The range of mobile grain sizes in Santaliestra is larger than in the upstream sections and includes up to very coarse gravel (<34 mm). This is a consequence of a much higher slope (about double that of the other sections) and smaller particle size corresponding to the lower percentiles of the GSD (regarding the upstream Campo sections). So, in relative terms, we conclude that in the River Ésera, the maximum hydropreach \(Q_c\) from the Campo HP plant should be competent in mobilising the finer size fractions of the bed, even 17 km downstream, a condition termed partial transport (Wilcock and McArdell, 1997).

Similar conclusions were drawn from an analogous study in another Pyrenean river (the Upper Cinca) under frequent hydropreaching (López et al., 2020); of five sections downstream of the HP plant, only the one closest to the plant was predicted to have significant sediment movement caused by the maximum hydropreach (its associated threshold of motion corresponds to \(D_{10} = 20\) mm). For the rest of the downstream sections, the threshold of sediment motion corresponded to values much lower than \(D_{95}\) of the surface GSD (varying between 0.5 mm and 11 mm). In contrast, in the present study of the River Ésera, it is precisely the section furthest downstream that is most affected. This is explained by the particular characteristics (geomorphology and bed surface sediment) of both sections. In the case of the Upper Cinca, the most mobilised section presented a narrower channel, high bed slope and a finer grain-size distribution than in the other downstream sections. As shown above, in the River Ésera, however, the Santaliestra section has a comparatively much higher slope and smaller particle size (for the lower percentiles of the GSD) with respect to the upstream sections. This was also observed in the Upper Noguera Pallaresa, another of the many Pyrenean rivers affected by hydropreaching, in which sand and fine gravel, stored in patches, and medium and coarse pebbles are winnowed by hydropreached flows (Vericat et al., 2020) until natural floods provide fresh fine sediment from upstream.

In the particular case of the River Ésera, tributaries downstream from the Campo Downstream section supply relevant amounts of water and, eventually, sediment. As has been introduced before, as an example, the flood registered on 15th October 2018 had a peak of 57 m\(^3\) s\(^{-1}\) at the Campo gauging station and 102 m\(^3\) s\(^{-1}\) at the Santaliestra gauging station. This difference is mainly attributed to the role of tributaries. In the same way, tributaries supply sediment and will have a major role on supplying sediment in the downstream sections, thus controlling sediment availability. However, in other gravel-bed streams exposed to hydropreaching, bed stability (i.e. scarce or null mobility) can be reinforced by hydropower regulation and extended downstream from the dam (e.g. Sear, 1992, 1995).
The impact of a dam associated with a hydroelectric power plant on bedload sediment transport is decisive for the formation of a coarse surface layer. In our case, flow releases are controlled by a system of four reservoirs located upstream of the Campo sections (the furthest one is about 40 km away and the volume of the reservoirs varies between 0.01 hm\(^3\) and 3.1 hm\(^3\)), a fact that has a direct impact on the supply of sediment from upstream. Lastly, despite peak Q corresponding with hydropoeaking in the River Ésera and the Upper Cinca having a low impact on the coarse surface layer, as described by Vericat et al. (2020) in the Noguera Pallaresa River, the condition of partial mobility that is attained (i) in reaches close to the HP plant, (ii) in reaches showing finer grain sizes (e.g. immediately downstream from tributaries), and/or (iii) during other periods or conditions (e.g. after flood events supplying fine materials from upstream) is significant in determining the frequency and extent of benthic disturbance (e.g. Gibbins et al., 2007; Wilcock et al., 2009; Schütting et al., 2016). Hence, it should not be neglected when assessing the effects of such flow pulses on the overall ecosystem behaviour.

5. Conclusions

This study brings valuable knowledge regarding the spatial variability of bed-material entrainment caused by hydropoeaking along a 17-km channel segment of the River Ésera. The use of three equations of particle entrainment, representing different conditions of initiation of motion (i.e. purely size-selective entrainment and different levels of partially size-selective entrainment) plus an equation developed by means of 491 entrainment observations allowed the critical analysis of the threshold of sediment motion in four study sections. The entrainment observations corresponded to an extensive database of various rivers worldwide, compiled for this study. The comparison between these predictions and six real entrainment observations in the River Ésera, acquired from tracked particles, indicates that the analysed models considerably overestimate the threshold of motion compared to real mobility conditions. These real mobility observations are aligned following the lower envelope of the cloud given by the entrainment observations of the extensive database. Therefore, the regression equation fitted to the tracer data obtained in this study is chosen as alternative predictor. This equation shows partially size-selective entrainment, in which only the finer size fractions of the bed are mobilised during hydropoeaking, and this condition is only reached in the section furthest to the hydropower plant (Santaliestra).

Channel geometry and relative location of the sections in the reach are key aspects when assessing downstream changes of sediment entrainment. Our study shows the effect of channel slope on mobilisation of bed material. The steepest section is capable of reaching the threshold of motion of the coarser bed material during relative low floods (lower than the annual flood), while more gentle reaches require less frequent (higher than the annual flood) but larger peak flows to reach this condition. Hydropoeaking in the River Ésera impacts the steepest and the furthest section from the hydropower plant and, as stated, affects only the finer fraction of grain-size distribution. The fine sediments eventually supplied by the floods of the intermediate tributaries are gradually entrained by the continuous action of the hydropoeaking, thus establishing cycles that oscillate between different levels of availability and depletion of the fine sediment. So, mobility resulting from hydropoeaking has a low impact on the coarser particles of the bed surface and the overall bedload flux of the river, but entrainment of the finest grains may help explain the extent of benthic disturbance in hydropoeaked rivers, as has been reported elsewhere. Future research in the study reach will be carried out to address questions beyond those presented here with the objective to study spatial and temporal changes on river-bed dynamics (i.e. armouring, imbrication, porosity) associated to hydropoeaking, and also to determine the role of the shape of the hydropoeaks on channel hydraulics and mobility along the 17 km channel segment.

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CRediT authorship contribution statement

Raúl López: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Fanny Ville: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Celso Garcia: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. Ramon J. Batalla: Conceptualization, Investigation, Supervision, Writing – review & editing. Damìà Vericat: Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing.

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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