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# 1 **Measurements of bedload sediment transport with an Acoustic Doppler** 2 **Velocity Profiler (ADVP)**

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## 11 **ABSTRACT (250 words)**

12 Acoustic Doppler Velocity Profilers (ADVP) measure the velocity simultaneously in a  
13 linear array of bins. They have been successfully used in the past to measure three-  
14 dimensional turbulent flow and the dynamics of suspended sediment. The capability  
15 of ADVP systems to measure bedload sediment flux remains uncertain. The main  
16 outstanding question relates to the physical meaning of the velocity measured in the  
17 region where bedload sediment transport occurs. The main hypothesis of the paper,  
18 that the ADVP measures the velocity of the moving bedload particles, is validated in  
19 laboratory experiments that range from weak to intense bedload transport. First, a  
20 detailed analysis of the raw return signals recorded by the ADVP reveals a clear  
21 footprint of the bedload sediment particles, demonstrating that these are the main  
22 scattering sources. Second, time-averaged and temporal fluctuations of bedload  
23 transport derived from high-speed videography are in good agreement with ADVP  
24 estimates. Third, ADVP based estimates of bedload velocity and thickness of the  
25 bedload layer comply with semi-theoretical expressions based on previous results. An  
26 ADVP configuration optimized for bedload measurements is found to perform only  
27 marginally better than the standard configuration for flow measurements, indicating  
28 that the standard ADVP configuration can be used for sediment flux investigations.  
29 Data treatment procedures are developed that identify the immobile-bed surface, the  
30 layers of rolling/sliding and saltating bedload particles, and the thickness of the  
31 bedload layer. Combining ADVP measurements of the bedload velocity with  
32 measurements of particle concentration provided by existing technology would  
33 provide the sediment flux.

34

35

**36KEY WORDS**

37bedload transport, acoustics, three-dimensional acoustic Doppler velocity profiler (3D-  
38ADVP), digital videography, particle velocimetry, optical flow

39

**40HIGHLIGHTS**

41 1. Signature of signal, simultaneous video analysis and agreement with semi-theoretical  
42 formulae demonstrate that ADVP can measure bedload velocities and bedload layer  
43 thickness.

44 2. ADVP measures time-averaged and turbulent velocities of bed load particles.

45 3. ADVP analysis identifies immobile-bed surface, and layers of rolling/sliding and  
46 saltating bedload.

## 47INTRODUCTION

### 48Problem definition

49Knowledge of the quantity of sediment transported in rivers is of paramount importance, for  
50example for understanding and predicting morphological evolution, hazard mapping and  
51mitigation, or the design of hydraulic structures like bridge piers or bank protections. In spite  
52of this importance, measurement of the sediment flux is notoriously difficult, especially  
53during high flow conditions when most sediment transport occurs.

54 The sediment flux per unit width can be expressed as:

$$55 \quad q_s = \int_{z_b}^{z_s} u_s c_s dz \quad (1)$$

56where  $z_s$  is the water surface level,  $z_b$  the immobile bed level,  $u_s$  the sediment velocity, and  $c_s$   
57the sediment concentration. The total sediment flux is the most relevant variable with respect  
58to the river morphology. It is, however, often separated in fluxes of suspended load sediment  
59transport and bedload sediment transport. Suspended load refers to sediment particles that are  
60transported in the body of the flow, being suspended by turbulent eddies. Because of their  
61small size – and thus their small Stokes number – suspended particles tend to follow the flow  
62streamlines, and thus their velocities are close to the velocities of the turbulent flow. In  
63contrast, bedload involves larger sediment particles that slide, roll and saltate on the bed, thus  
64remaining in close contact with it. The friction and the frequent collisions of bedload particles  
65with the granular bed reduce considerable their velocity. Because of drag forces, fluid  
66velocities may also be reduced inside the bedload layer.

67 Accurate measurement of bedload transport has long been a goal of river and coastal  
68scientists and engineers (e.g., Mulhoffer 1933). Conventional measurements with physical  
69samplers are limited in spatial and temporal resolution, are cost prohibitive due to substantial  
70manual labour, and can be difficult and/or dangerous to conduct during high channel-forming

71flows when most bed material transport occurs. Videography techniques have been developed  
72for laboratory settings and well-controlled flows (Drake et al. 1988, Radice et al. 2006,  
73Roseberry et al. 2012, Heyman 2014), but are hindered when intense suspended sediment  
74transport occurs due to the turbidity of the water. They are particularly difficult to use in the  
75field especially under high flow conditions when intense sediment transport occurs.  
76Consequently, little is known about the temporal and particularly the spatial distribution of  
77fluvial bedload, other than the recognition that the spatiotemporal distribution of bed material  
78transport determines channel form (Ferguson et al. 1992, Church 2006, Seizilles et al. 2014;  
79Williams et al. 2015).

80 Acoustic Doppler Current Profiler (ADCP) backscatter intensity and/or attenuation  
81have been used to estimate suspended sediment concentration and grain size (e.g., Guerrero et  
82al. 2011; Guerrero et al. 2013; Moore et al. 2013; Latosinski et al. 2014; Guerrero et al.  
832016). Rennie et al. (2002), Rennie and Church (2010), and Williams et al. (2015) have used  
84the bias in ADCP bottom tracking (Doppler sonar) as a measure of apparent bedload velocity.  
85Due to the diverging beams of ADCP's, this technique may provide only an indication of  
86bedload particle velocities averaged over the bed surface insonified by the four beams. This  
87technique also does not provide the thickness and concentration of the active bedload layer,  
88which are required to determine the bed load flux (Rennie and Villard 2004; Gaueman and  
89Jacobson 2006).

90 ADVP's, which use beams that converge in one single area of measuring bins, have  
91commonly been used to investigate turbulent flows (Figure 1). Their application range has  
92recently been extended to the investigation of the dynamics of transported sediment, mainly  
93transport in suspension (e.g., Crawford and Hay 1993; Thorne and Hardcastle 1997; Shen and  
94Lemmin 1999; Cellino and Graf 2000; Stanton 2001; Smyth et al. 2002; Thorne and Hanes

952002, Hurther et al. 2011; Thorne et al. 2011; Thorne and Hurther 2014). The present paper  
96focuses on their use for the measurement of bedload sediment transport.

### 97ADVP: working principle and state-of-the-art

98 The working principle of ADVP has been detailed previously (e.g., Lemmin and  
99Rolland 1997 ; Hurther and Lemmin 1998; Thorne et al. 1998; Shen and Lemmin 1999;  
100Stanton and Thornton 1999; Stanton 2001; Zedel and Hay 2002). The main features of the  
101ADVP's working principle that are required for making the present paper self-contained are  
102summarized hereafter. An ADVP consists of a central beam emit transducer surrounded by  
103multiple fan-beam receive transducers (Figure 1a). The instrument is typically set up on a  
104fixed mount pointing down toward the bed, and measures simultaneously velocities in the  
105water column situated between the emitter and the bed. This water column is divided in  
106individual bins of O(mm). The profiling range, i.e. the height of the measured water column,  
107is typically of O(m). The emit transducer sends a series of short acoustic pulses vertically  
108down towards the bed with a user-defined pulse-repetition-frequency (PRF) and pulse length.  
109These pulses are reflected by scattering sources in the water, and a portion of this scattered  
110sound energy is directed toward the receive transducers. Turbulence-induced air bubble  
111microstructures in sediment-free clear water (Hurther, 2001) or sediment particles in  
112sediment-laden flows (Hurther et al. 2011) can be scattering sources of this instrument. For  
113each bin in the water column, the backscattered signal recorded by each of the receivers can  
114be written as:

$$115 \quad a(t) = A \cos[2\pi(f_0 + f_D)t] \quad (2)$$

116A is the amplitude of the recorded signal and  $f_D$  the Doppler frequency shift. The latter is  
117proportional to the velocity component directed along the bisector of the backscatter angle  
118(Figure 1b):

$$f_D = 2 \frac{f_0}{c} \vec{V} \cdot \vec{e}_B \quad (3)$$

119

120The speed of sound in water is indicated by  $c$ ,  $\vec{V}$  is the vectorial velocity of the scattering  
 121source,  $\vec{e}_B$  the unit vector along the bisector of the backscatter angle for the considered bin.  
 122In order to compute  $f_D$ , the recorded signal  $a(t)$  is typically demodulated into in-phase and  
 123quadrature components, represented by  $I(t)$  and  $Q(t)$ , measured in volt. The Doppler  
 124frequency  $f_D(t)$  corresponds to the frequency of these oscillating  $I(t)$  and  $Q(t)$  signals. The  
 125demodulation into in-phase and quadrature parts is necessary to determine the sign of  $f_D$ . The  
 126quasi-instantaneous Doppler frequency is typically computed with the pulse-pair algorithm  
 127using NPP (number of pulse-pairs) samples of  $I(t)$  and  $Q(t)$  (Miller and Rochwarger 1972;  
 128Lhermitte and Serafin, 1984; Zedel et al. 1996; Zedel and Hay 2002):

$$\hat{f}_D = \frac{PRF}{2\pi} \tan^{-1} \left[ \frac{\sum_{s=1}^{NPP-1} Q_s I_{s+1} + I_s Q_{s+1}}{\sum_{s=1}^{NPP-1} I_s I_{s+1} + Q_s Q_{s+1}} \right] \quad (4)$$

129

130The symbol  $\hat{\phantom{x}}$  denotes an average over NPP time samples, and  $s$  denotes a time index. NPP  
 131has to be chosen high enough to assure second-order stationarity, but low enough so that  
 132NPP/PRF remains small compared to the characteristic timescale of the investigated turbulent  
 133flow. Utilization of at least three receive transducers allows for measurement of all three  
 134velocity components. Beam velocities are converted to Cartesian coordinates using a beam  
 135transformation matrix specific for the beam geometry.

136

[Figure 1]

137 Acoustic Concentration and Velocity Profilers (ADCP), which integrate an ADVP and  
 138an Acoustic Backscatter System (ABS), have been successfully used to investigate suspended  
 139sediment fluxes, defined as the product of sediment velocity and sediment concentration

140(Equation 1). The ADVP measures the velocity of the suspended sediment, which is assumed  
141to be equal to the flow velocity. The ABS provides the particle concentration in bins  
142throughout a profile is obtained based on the range-gated acoustic backscatter intensity and/or  
143attenuation (e.g., Crawford and Hay 1993; Thorne and Hardcastle 1997; Shen and Lemmin  
1441999; Thorne and Hanes 2002; Hurther et al. 2011; Thorne et al. 2011; Thorne and Hurther  
1452014; Wilson and Hay 2015; Wilson and Hay 2016). These measurements have permitted  
146direct examination of suspended sediment transport as a function of flow forcing. For  
147example, Smyth et al. (2002) used an ADCP system to document periodic sediment  
148suspension associated with turbulent vortex shedding from ripples in a wave bottom  
149boundary layer.

150 A broadband multifrequency ADCP, called MFDop, capable of 0.0009 m vertical  
151resolution at 85 Hz has recently been developed by Hay et al. (2012a,b,c), that allows for  
152estimation of both particle concentration and grain size (Crawford and Hay 1993; Thorne and  
153Hardcastle 1997; Wilson and Hay 2015; Wilson and Hay 2016). For this system, velocities  
154measured in bins within 0.005 m of a fixed bed were deemed to be negatively biased, based  
155on nonconformity with the profiles of both log-law velocity and phase shift expected in a  
156wave bottom boundary layer. This bias occurred largely because equal travel time paths  
157between send and receive transducers included bottom echo for bins close to the bed (Figure  
1581a,b). However, the system was able to measure the bed velocity (of an oscillatory cart) based  
159on Doppler processing of the signal at the observed bottom range.

160 Hurther et al. (2011) have recently developed ACVP, which combines an ADVP with  
161advanced noise reduction for turbulence statistics (Blanckaert and Lemmin 2006, Hurther and  
162Lemmin 2008) with the ABS system developed by Thorne and Hanes (2002). The ACVP  
163measures co-located, simultaneous profiles of both two-component velocity and sediment  
164concentration referenced to the exact position at the bed. Measurements are performed with



165high temporal (25 Hz) and spatial (bin size of 0.003 m) resolution. Sediment concentration  
166profiles are determined by applying the dual-frequency inversion method (Bricault 2006;  
167Hurther et al. 2011), which offers the unique advantage of being unaffected by the non-linear  
168sediment attenuation across highly concentrated flow regions, and thus to allow also for the  
169measurement of high sediment concentrations near the bed where the bedload transport  
170occurs. The acoustic theory underpinning the dual-frequency inversion method is based on  
171the condition of negligible multiple scattering (Hurther et al. 2011). Although this condition is  
172probably violated in the bedload layer, Naqshband et al. (2014b, their Figure 12) have  
173successfully applied the method to estimate the sediment concentration all through the  
174bedload layer onto the immobile bed, where a bulk concentration of  $\rho_s(1-\varepsilon) = 1590 \text{ kg m}^{-3}$   
175was correctly measured. Here  $\varepsilon$  is the porosity of the immobile sediment bed. These results  
176indicate that the theoretical condition of negligible multiple scattering can be relaxed and that  
177the dual-frequency inversion method is also able to measure the high sediment concentrations  
178in the bedload layer. The ACVP has been used to measure velocity, concentration profiles and  
179sediment fluxes over ripples under shoaling waves (Hurther and Thorne 2011) and over  
180migrating equilibrium sand dunes (Naqshband et al. 2014a,b). An acoustic interface detection  
181method was used to identify the immobile bed and the suspended load layer and a layer in  
182between with higher sediment concentrations (Hurther and Thorne 2011; Hurther et al. 2011).  
183Hurther and Thorne (2011) acknowledged uncertainty in the identification of the near-bed  
184layer with high sediment concentration, but found that the estimated sediment flux matched  
185estimates based on ripple migration. They termed this layer the “near-bed load layer”.  
186Naqshband et al. (2014b) also found that sediment fluxes in this layer were in line with  
187estimates for bedload transport. Measured velocities in this layer were found to deviate from  
188the logarithmic profile often observed above plane immobile beds. These deviations were  
189attributed to the presence of the high sediment concentration. There remains uncertainty,

190however, in the physical meaning of the velocities measured in this non-logarithmic velocity  
191layer. This uncertainty is acknowledged by Naqshband et al. (2014b), who note that it is  
192difficult to validate whether this layer corresponds to the physical bedload layer, because no  
193data could be collected to trace sediment movement or sediment paths.

194 These recent developments clearly demonstrate that ADCP systems are capable of  
195measuring suspended load sediment flux, but that the capability of ADCP systems to measure  
196bedload sediment flux remains uncertain. The ABS component of the system's ability to  
197measure sediment concentration in the bedload layer has been demonstrated (Naqshband et  
198al. 2014b). The main outstanding question relates to the physical meaning of the velocity  
199measured by the ADV component of the system in the region where bedload sediment  
200transport occurs (Equation 1).

201 Other issues remain that render uncertain the capability of ADV systems to measure  
202bedload. First, 3D acoustic velocity profilers are usually configured to obtain optimal  
203measurements of flow properties. Typically, an ADV is set up such that the region of overlap  
204of the emit and receive beams maximizes the profiling range and includes the entire water  
205column, such that optimal measurements of flow properties are obtained in the core of the  
206water column (Figure 1a). This means that the axis of the receiver, where the receivers'  
207sensitivity is highest, intersects theinsonified water column in a bin displaced above the bed  
208in the body of the water column. Moreover, the acoustic power is optimized in the water  
209column, in order to maximize the signal-to-noise ratio (SNR). This commonly leads to a  
210power level of the backscatter for bins near the bed that is outside the recording range of the  
211receivers, because the acoustic backscatter from bedload sediment particles is much greater  
212than from scatterers in the water (Figure 2). Second, there is potential for contamination of  
213near-bed bins by high intensity scatter from the immobile bed with equivalent acoustic travel  
214time between the send and receive transducers (Figure 1a,b). As discussed above, this can

215result in negative bias of particle velocities estimated in near-bed bins (Hay et al. 2012a).  
216This can also result in saturation of the first bin echo, which makes difficult the estimation of  
217Doppler velocity and particle concentration. Similarly, highly concentrated bedload in the  
218first bin can saturate the echo from the first bin. Third the nature of bedload itself renders the  
219scattering and propagation within the bedload layer complex. The usual scattering model  
220assumes a low concentration of scatterers in the water. This assumption is most probably  
221violated in the bedload layer. Moreover, bedload particle sizes and velocities are variable,  
222thus bedload transport tends to be a heterogeneous phenomenon, which broadens the received  
223frequency spectrum and could render Doppler velocity estimates imprecise. Bed material  
224particle size distributions tend to be log-normal, and bedload particle velocity distributions  
225can be left skewed gamma (Drake et al. 1988, Rennie and Millar 2007), exponential  
226(Lajeunesse et al. 2010; Furbish et al. 2012) or Gaussian (Martin et al. 2012, Ancy and  
227Heyman 2014). Conventional Doppler signal processing techniques find the mean velocity in  
228a presumed homogenous volume of particles, and this estimate may not best characterize the  
229bedload.

230 [Figure 2]

### 231Hypothesis and detailed objectives

232 The main objective of the present paper is to demonstrate the capability of ADV  
233systems to measure bedload sediment transport, by investigating the physical meaning of the  
234velocity measured with the ADV in the region where bedload sediment transport occurs. In  
235all experiments without sediment transport reported in this paper, the ADV resolved the law  
236of the wall logarithmic velocity profile, including very close to the bed (Figure 3a). On the  
237contrary, in all experiments with bedload sediment transport reported in this paper, velocities  
238in the near-bed region where bedload sediment transport occurs were found to deviate from  
239the logarithmic profile (Figure 3a,b), similar to observations Naqshband et al. (2014b). The

240main hypothesis of the present paper is that the ADVP measures the velocity of the sediment  
241particles moving as bedload in this near-bed region. The hypothesis is tested over a range of  
242bedload transport conditions for a gravel-sand bed material mixture in a mobile bed flume. In  
243this paper we focus on measurement of bedload particle velocities and the thickness of the  
244bed load layer. In order to validate the hypothesis, three strategies are followed. First, a  
245detailed analysis is performed of the raw  $I(t)$  and  $Q(t)$  signals recorded by the ADVP's  
246receivers that reveals a clear footprint of the bedload sediment particles. Second,  
247simultaneous observations of bedload sediment transport are conducted with high speed  
248digital videography. Third, ADVP based estimates of the bedload velocities and thickness of  
249the bedload layer are compared to semi-theoretical formulae based on previous results.

250 The present research makes use of an ADVP configuration that is specifically designed  
251and tested for measurement of bedload transport. As described below, the instrument beam  
252geometry is designed such that it is most sensitive in the first bin above the bed, and the  
253acoustic power is chosen such that backscattered signal remains within the recording range of  
254the receivers in the bedload region (Figure 2). The bedload measurement capabilities of this  
255optimised ADVP configuration and the standard ADVP configuration for flow measurements  
256are also compared.

257 [Figure 3]

## 258METHODS

### 259Experimental program

260The ADVP's potential to measure bedload was tested in a flume at École Polytechnique  
261Fédéral de Lausanne (EPFL). The flume was 0.50 m wide with zero slope, and the test  
262section was 6.6 m downstream of the flume inlet. The bed sediment was poorly sorted ( $\sigma =$   
263 $0.5 \times (d_{84}/d_{50} + d_{50}/d_{16}) = 4.15$ , where  $d_i$  represents the  $i^{\text{th}}$  percentile grain size) with median,

264mean, and 90<sup>th</sup> percentile grain sizes of  $d_{50}=0.0008$  m,  $d_m = 0.0023$  m and  $d_{90} = 0.0057$  m,  
265respectively (Leite Ribiero et al. 2012). The critical shear velocity for the initiation of  
266sediment transport for  $d_{50}$  and  $d_m$  are  $0.020$  m s<sup>-1</sup> and  $0.039$  m s<sup>-1</sup>, respectively, based on the  
267Shields criterion (Shields 1936). No sediment was fed to the flume or recirculated during the  
268tests. The transported sediment originated from the entrance reach of the flume, where  
269erosion locally occurred. Between experiments, the scour hole was replenished to compensate  
270for sediment lost from the system. Due to the inherent intermittency and variability of  
271sediment transport (Drake et al. 1988, Frey et al. 2003, Singh et al 2009; Heyman et al. 2013;  
272Mettra 2014) and the formation of small dunes, bed levels varied during some of the tests.  
273These conditions were chosen on purpose, in order to provide a broad range of experimental  
274conditions, and to test the robustness of ADVP bedload measurement in quasi-realistic  
275conditions. Table 1 summarizes the conditions in all experiments.

276 The main series of tests utilized simultaneously both the ADVP in a configuration  
277optimized for the measurement of bedload transport (Figure 1b), and a digital video camera  
278for bedload measurement (Figure 1c). The nominal flow depth was 0.24 m, but varied  
279slightly between test runs (Table 1). This flow depth was obtained by regulating a weir at the  
280downstream end of the flume. Three bedload transport conditions were tested by changing the  
281flow rate in the flume. The low flow run Q630 ( $Q = 0.063$  m<sup>3</sup> s<sup>-1</sup>) resulted in dune transport of  
282fine sediment (smaller than  $d_m$ ) that led to gradual armouring of the bed. The medium flow  
283run Q795 ( $Q = 0.080$  m<sup>3</sup> s<sup>-1</sup>) produced partial transport conditions, with coarser particles in  
284transport, but many of the coarse particles on the bed surface were stable at any particular  
285instant. Lastly, the high flow run Q1000 ( $Q = 0.100$  m<sup>3</sup> s<sup>-1</sup>) broke up the armour bed and the  
286entire bed surface and all grain sizes were mobile throughout the run. At these highest flow  
287conditions, the saltation height and length of bedload particles were considerably increased,  
288but suspended load sediment transport remained negligible. The Shields parameters based on

289  $d_{50}$  and  $d_m$  varied from 0.07 to 0.24 and from 0.02 to 0.08, respectively, in these experiments.  
290 The sediment transport behaviour was in agreement with expectations based on the Shields  
291 parameter and the critical shear velocity for the different grain sizes in the sediment mixture  
292 (Bose and Dey 2013). Videos of the three sediment transport conditions are available as  
293 supporting information. Measurements with high and low acoustic power were utilized and  
294 compared for each bedload transport condition (Figure 2). The high acoustic power  
295 corresponds to the standard ADVP setting, where SNR is optimized in the main body of the  
296 water column, but leads to frequent saturation of the signal in the near-bed area. The low  
297 acoustic power minimizes potential for acoustic saturation of the near-bed layer. It is  
298 expected to improve measurements in the near-bed layer, but leads to a lower SNR in the  
299 main body of the water column. The labels of experiments with high and low acoustic power  
300 are appended with H and L, respectively (Table 1).

301 [Table 1]

302 A second series of tests was also collected with the ADVP in its standard configuration  
303 optimized for flow measurements in the body of the water column (Figure 1a), and without  
304 simultaneous videography (Table 1). The purpose of this series was to compare the  
305 capabilities of the standard ADVP configuration and the one optimized for bedload  
306 measurements, and to extend the investigation to a broader range of hydraulic conditions.  
307 Experiments were performed with nominal flow depths of 0.14 m and 0.24 m. For each of  
308 these flow depths, 10 different discharges were tested (Table 1). In the tests with 0.14 m flow  
309 depth, discharge ranged from  $0.013 \text{ m}^3 \text{ s}^{-1}$  to  $0.060 \text{ m}^3 \text{ s}^{-1}$ , shear velocity from  $0.009 \text{ m s}^{-1}$  to  
310  $0.052 \text{ m s}^{-1}$  and the Shields parameters based on  $d_{50}$  and  $d_m$  from 0.006 to 0.20 and from 0.002  
311 to 0.07, respectively. In the tests with 0.24 m flow depth, discharge ranged from  $0.020 \text{ m}^3 \text{ s}^{-1}$   
312 to  $0.100 \text{ m}^3 \text{ s}^{-1}$ , shear velocity from  $0.012 \text{ m s}^{-1}$  to  $0.062 \text{ m s}^{-1}$  and the Shields parameter based  
313 on  $d_{50}$  and  $d_m$  from 0.01 to 0.29 and from 0.003 to 0.10, respectively. At the lowest discharge,

314no sediment transport occurred, whereas generalized and intense sediment transport occurred  
315at the highest discharge. Again, the sediment transport behaviour was as expected based on  
316the Shields parameter and the critical shear velocity for the different grain sizes in the bed  
317mixture (Bose and Dey 2013). The runs with 0.24 m flow depth encompassed the hydraulic  
318conditions investigated in the main series with optimized ADVP configuration and  
319simultaneous videography, which facilitates comparison.

### 320ADVP configuration and data analysis procedures

321The ADVP utilized for this research has been developed at EPFL. Its working principle has  
322been detailed in Rolland and Lemmin (1997), Hurther and Lemmin (1998, 2001), Hurther  
323(2001), and Blanckaert and Lemmin (2006). The instrument consists of a central emit  
324transducer of diameter 0.034 m and of carrier frequency,  $f_0 = 1$  MHz, with beam width of  
325 $1.7^\circ$ , and four  $30^\circ$  fan-beam receive transducers that are  $30^\circ$  inclined from the vertical (Figure  
3261). In all experiments, PRF was set to 1000 Hz, and NPP to 32, yielding a sampling frequency  
327of  $\text{PRF}/\text{NPP} = 31.25$  Hz for the quasi-instantaneous Doppler frequencies and velocities. A  
328pulse length of  $5 \mu\text{s}$  was chosen, yielding a vertical resolution of velocity bins of about 0.004  
329m. A time series of more than 10 min was collected for each test condition, which was  
330sufficient to obtain statistically stable measurements of the flow and sediment transport under  
331quasi-steady conditions. Blanckaert and de Vriend (2004) and Blanckaert (2010)  
332discuss in detail the uncertainty in the flow quantities measured with this ADVP. They report  
333a conservative estimate of 4% uncertainty in the streamwise velocity  $u$ .

334 In the main series of tests (Table 1), the ADVP configuration was optimized to measure  
335bedload transport, as explained hereafter (Figure 1b). The ADVP was configured  
336symmetrically, with horizontal and vertical distances between emit and receive transducers of  
3370.1305 m and 0.0304 m, respectively. The ADVP was immersed in the flow, with the emit  
338transducer 0.185 m above the nominal bed level. With this configuration, the centre of the

339 receive beam was focused on the bed level. This ensured that the ADV was most sensitive in  
340 the vicinity of the bedload layer. This configuration, however, did not allow for  
341 measurements in the upper half of the water column (Figure 1b).

342 In the second series of experiments (Table 1), the standard ADV configuration was  
343 used (Figure 1a). Receivers symmetrically surrounded the emit transducer at horizontal and  
344 vertical distances of 0.1343 m and 0.0295 m, respectively. In order to measure the entire  
345 water column, the ADV was placed about 7 cm above the water surface in a water-filled box  
346 that was separated from the flowing water with an acoustically transparent mylar film (Figure  
347 1a). The box induces perturbations of the flow in a layer with a thickness of about 0.02 m near  
348 the water surface. In the experiments with flow depth of 0.14 m, the center of the receive  
349 beam was focused on the bed level. In the experiments with flow depth of 0.24 m, it was  
350 focused in the core of the water column, about 0.10 m above the bed (Figure 1a).

351 The acoustic footprint on the bed of the emitted beam is circular with a diameter that  
352 ranges from about 0.045 m in the experiments with 0.14 m flow depth to about 0.055 m in the  
353 experiments with 0.24 m flow depth (Figure 1). This means that the ADV does not resolve  
354 grain scale processes, but processes at a characteristic scale of about 0.05 m.

355 The standard ADV data analysis procedure considers two output quantities: the  
356 magnitude of the backscattered signal recorded by the receive transducers (Figure 2) and the  
357 time-averaged velocity estimated with the pulse-pair algorithm (Equation 4, Figure 3).

358 The profile of the time-averaged longitudinal flow velocity is typically logarithmic in  
359 the vicinity of the bed in cases without bedload sediment transport (Nezu and Nakagawa,  
360 1993). In order to identify the logarithmic part, the measured time-averaged velocity is  
361 plotted as a function of  $\log(30z/k_s)$ , where  $z$  is the distance in meter above the immobile bed,  
362 and the equivalent grain roughness  $k_s$  is taken as 0.01 m (Figure 3). In order to avoid



363 singularities, the bin containing the surface of the immobile bed has been plotted at  $z = 0.001$   
364 m. The profile of the time-averaged velocity as a function of  $\log(30z/k_s)$  also identifies the  
365 near-bed region where the measured velocities are smaller than the logarithmic profile in  
366 cases with bedload sediment transport, similar to observations by Naqshband et al. (2014b).  
367 In this non-logarithmic near-bed layer, the measured velocity profiles typically have an S-  
368 shape (Figure 3). As mentioned before, the main hypothesis of the present paper is that the  
369 ADVP measures the particle velocities in this near-bed zone. Sediment is predominantly  
370 moving as bed load transport in the investigated experiments. Most particles are  
371 intermittently entrained from the immobile bed by the flow, slide and roll over the immobile  
372 bed, and finally immobilize again. The velocity of these sliding and rolling particles is  
373 generally smaller than the velocity of the surrounding fluid, due to momentum extraction by  
374 inter-particle collisions, inertia of the sediment particles, and friction on the granular bed. The  
375 difference between the velocities of particles and the entraining flow is called the slip  
376 velocity (Nino and Garcia 1996; Muste et al. 2009). It is assumed that the extrapolated  
377 logarithmic profile provides an estimate of the velocity of the entraining flow. An increase in  
378 number of moving particles can be assumed to increase the momentum extraction due to  
379 inter-particle collision, and hence also the slip velocity. Therefore, the dominant bed load  
380 transport is assumed to occur at the elevation of maximum slip velocity, which approximately  
381 coincides with the inflection point in the S-shaped near-bed velocity profile (Figure 3b). By  
382 definition, this inflection point occurs where the second derivative of the velocity with  
383 respect to  $z$  vanishes. Some bedload particles saltate on the bed and reach higher elevations in  
384 the water column. Because saltating bedload particles are usually relatively small and their  
385 saltation length scale is longer with fewer inter-particle collisions than those of the rolling  
386 bedload particles, their velocity is closer to the velocity of the entraining fluid. As mentioned  
387 before, suspended load particles have negligible slip velocity and move at about the same

388velocity as the flow. Thus, the shape of the measured velocity profile identifies the layer with  
389rolling and sliding bedload transport, the layer with saltating bedload transport and the layer  
390with suspended load transport or clear water.

391 A critical issue in the identification of the different layers of sediment transport is the  
392identification of the elevation of the surface of the immobile bed, which by definition  
393corresponds to zero velocity. The accuracy in the identification of the immobile bed surface is  
394limited by the finite bin size of 0.004 m and by the fact that a natural sediment bed is not  
395perfectly planar. The best practice consists in identifying the bin in which the surface of the  
396immobile bed is situated, as illustrated in Figure 4. The upper part of that bin will be situated  
397in the flow. In case no bedload sediment transport occurs, the ADVP will measure zero  
398velocity in the bin containing the surface of the immobile bed, because the magnitude of the  
399raw signal backscattered on micro-air bubbles in the flowing water is much smaller than the  
400magnitude of the one backscattered on the immobile bed. If bedload sediment particles roll  
401and slide on the immobile bed within the bin containing the immobile bed, the ADVP will  
402measure a non-zero velocity, which corresponds to the average velocity of sediment particles  
403within that bin (Figure 4), i.e. this spatial average also includes areas of zero velocity  
404associated with immobile particles within the measuring area of the ADVP. The bin  
405containing the surface of the immobile bed is therefore identified as the bin with the  
406minimum non-zero velocity, as illustrated in Figures 3 and 4.

407 A second independent estimation of the bin containing the surface of the immobile bed  
408is obtained from the magnitude of the raw backscattered signal recorded by the receivers,  $I^2 =$   
409 $0.25 (I_1^2 + I_2^2 + I_3^2 + I_4^2)$  (Figure 2). Here,  $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$  are the raw in-phase components of the  
410demodulated signals recorded by each of the four receivers. The magnitude of the  
411backscattered signal relates to the concentration of the sediment particles, because sediment  
412particles backscatter considerably more acoustic energy than micro air-bubbles in the water

413column above (Hurther et al. 2011). Based on this heuristic definition, the bin containing the  
414immobile bed is assumed to correspond to the peak in the profile of the magnitude of the  
415backscattered signal (Figure 2). In the present paper, we have used the first estimation to  
416define the bin containing the surface of the immobile bed, and the second estimation for  
417validation purposes. In general, both estimation identified the same bin.

418 In the Q795L experiment shown in Figures 2 and 3b, the surface of the immobile-bed is  
419estimated within bin number 58, the sliding and rolling bedload is estimated in bin 57, and  
420the top of the saltating bedload in bin 55. These heuristic estimations are based on the shape  
421of the velocity profile as discussed earlier. In most experiments, however, the bed load  
422sediment transport caused variations in the elevation of the surface of the immobile bed  
423during the 10 min duration of the experiment. This is illustrated for experiment Q1000L in  
424Figure 5, which shows the temporal evolution of the magnitude of the raw backscattered  
425return signal,  $I^2 = 0.25 (I_1^2 + I_2^2 + I_3^2 + I_4^2)$ , during the 614 s measurement period. The figure  
426highlights the part of the water column between bin numbers 50 and 65 where the magnitude  
427of the backscattered raw return signal reaches maximum values. This range encompasses the  
428immobile bed, the assumed layers of rolling/sliding and saltating bedload, and part of the  
429clear water layer. Variations in the elevation of the surface of the immobile bed level are  
430clearly illustrated by the temporal evolution of the location where the maximum magnitude of  
431the raw return signal occurs. The bed level aggraded in the beginning of the test and reached  
432a maximum level after approximately 60 s. The bed level subsequently gradually lowered and  
433reached a quasi-constant level after approximately 165 s. Periods with quasi-constant  
434characteristics are first identified and isolated in each experiment (see Table 2 and detailed  
435Tables in the supporting information). For the Q1000L experiment shown in Figure 5, for  
436example, 5 periods of quasi-constant conditions are identified. The data analysis procedure of  
437the ADV measurements is performed separately for each of these periods. For each period

438of quasi-constant conditions the elevation of the surface of the immobile bed, the layer of  
439saltating bedload, the layer of rolling and sliding bedload, and the layer of sediment-free clear  
440water are defined based the data analysis procedures described above. These layers are  
441indicated in all relevant figures.

442

[Figure 5]

#### 443**Digital videography**

444A Basler A311f high-speed digital video camera was used to record images of the mobile bed  
445through the sidewall of the flume (Figure 1c). The images gave a distorted picture of the bed  
446(due to perspective) but were centred on the ADVP sample volume in the centre of the flume,  
447with a 0.122 m centreline longitudinal by 0.155 m transverse field of view. The images had  
448656x300 resolution, thus pixel size was approximately 0.0002x0.0005 m. The videography  
449maps the three-dimensional sediment motion on a horizontal plane, which is complementary  
450to the resolution in a vertical water column provided by the ADVP. Image exposure time was  
451300  $\mu$ s, and sampling rate was 111 Hz. Computer clock times were used to synchronize image  
452acquisition with ADVP data collection. Digital video images were orthorectified using a  
453projective transformation (Beutelspacher et al. 1999). Due to limitations in computer storage  
454and data transfer, digital videos with high temporal resolution could only be recorded for  
455maximum 10 seconds. During the 10-minute ADVP data collection, 10-second digital videos  
456were collected once every minute (Figure 5). The cumulative duration of the digital videos of  
457more than 110 seconds is long enough to obtain reliable estimates of the velocities of the  
458bedload particles. Two complementary image treatment algorithms were used.

459 In order to estimate the velocity of sediment particles, the robust open-source particle  
460tracking velocimetry (PTV) algorithm *PolyParticleTracker* was used (Rogers et al. 2007).  
461This algorithm is able to estimate the position and track several objects through frames with a

462sub-pixel resolution. The algorithm was specifically developed for tracking bright objects  
463over a complex background. The particle instantaneous velocities are then estimated by time  
464differentiation of the particle positions. Erroneous trajectories were filtered with techniques  
465commonly used in Particle Image Velocimetry. First, a maximum acceleration criterion of 40  
466 $\text{m s}^{-2}$  was defined for individual particles. Then, the angle between two successive velocity  
467vectors was limited to  $90^\circ$ . Particles are often found with velocities close to zero while  
468bouncing on the bed. In order to avoid sampling of these quasi-immobile bed particles that  
469only marginally contribute to the sediment flux, a minimum velocity threshold of  $0.04 \text{ m s}^{-1}$   
470was adopted. Full trajectories of particles, from entrainment to deposition were not always  
471recovered by the algorithm, mainly due to the presence of the noisy background composed of  
472resting particles. Moreover, not all of the moving particles were systematically detected. It  
473can be expected that especially the saltating bedload with relatively small grain size and  
474relatively high velocities was undersampled. Enough particle trajectories were correctly  
475recovered to provide a good estimate of the distribution functions of the sediment velocities  
476and the time-averaged velocity of the moving sediment particles. These quantities will be  
477shown and discussed in the section “Simultaneous videography”.

478       An instantaneous spatio-temporal quantification of the bedload layer velocities was,  
479however, not possible from the trajectories obtained with the PTV method, since not all of the  
480moving particles were systematically detected by the automated algorithm and since full  
481trajectories from entrainment to deposition were not always recovered. In order to estimate  
482bedload velocity time series in the ADV sample volume, a complementary analysis of the  
483digital video images was performed with the Optical Flow algorithm (Horn and Schunck  
4841981). This algorithm remedies the small sample limitation of the particle tracking  
485algorithm by computing for each pair of frames a dense 2D velocity field that reflects the

486local apparent motion in the image. The algorithm assumes that the intensity value  $I(x,y,t)$  of  
487each pixel follows a simple advection equation :

$$488 \quad \frac{\partial I}{\partial t} + u \frac{\partial I}{\partial x} + v \frac{\partial I}{\partial y} = \varepsilon \quad (5)$$

489where the problem unknowns are the velocity components  $u(x,y,t)$  and  $v(x,y,t)$  along the  $x$  and  
490 $y$  axes. The partial derivatives of  $I$  can be estimated directly from the video stream:  $\partial I/\partial t$  is  
491the temporal change in pixel intensity, and  $\partial I/\partial x$  and  $\partial I/\partial y$  are the spatial gradients in pixel  
492intensity. The Optical Flow method determines the velocity field  $(u,v)$  that minimize  $\varepsilon$ .  
493Intuitively, the apparent motion of an object is better appreciated by the human eye if it  
494contains high intensity gradients (border contrasts for instance). On the contrary, the motion  
495of objects with low contrast is difficult to estimate by the human eye. This is similar for the  
496Optical Flow method, which will perform better when  $\partial I/\partial x$  and  $\partial I/\partial y$  are larger. In case these  
497spatial gradients equal zero, the velocity field  $(u,v)$  is not uniquely determined by Equation  
498(5) and the problem is ill-posed. In this case, an additional constraint (also called a regularizer  
499Horn and Schunck 1981) needs to be imposed, usually based on the continuity of the velocity  
500field. The efficiency of this technique relies thus on the presence of strong intensity gradients,  
501as those frequently observed at object edge contours. The Optical Flow algorithm can be  
502expected to be especially appropriate for the largest bedload particles that roll and slide on the  
503immobile bed, because these particles form well distinguishable contours in the digital  
504images that yield large gradients  $\partial I/\partial x$  and  $\partial I/\partial y$ . Faster and smaller bedload particles can be  
505expected to be undersampled due to their weaker intensity gradients. This algorithm has been  
506successfully applied in numerous applications, including flow reconstruction from Particle  
507Image Velocimetry techniques (Ruhnau et al. 2005, Heitz et al. 2008), but it has yet rarely  
508been applied to the estimation of sediment motion (Spies et al. 1999, Klar et al. 2004). Here,  
509the Optical Flow algorithm has been applied to investigate the time-resolved velocity of the

510bedload particles inside the ADVP sample volume. The particle velocities have been  
511estimated from the digital video images with the open access Matlab implementation of the  
512Lukas-Kanade Method (Lucas and Kanade, 1981) by Stefan M. Karlsson and Josef Bigun  
513and available at <http://www.mathworks.com/matlabcentral/fileexchange/40968>. In order to  
514improve the accuracy and to reduce noise, the velocity field was averaged on a 70x70 grid  
515overlapping the original 656x300 pixels images. The local sediment velocity spatially-  
516averaged within the footprint of the ADVP's measuring beam at the bed was then obtained by  
517averaging the 70x70 Optical Flow velocity field using a Gaussian kernel centred on the  
518volume. It is worth noting that this spatial average also includes areas of zero velocity  
519associated with immobile particles, and thus reflects the average bed velocity. This is  
520different from the sediment velocities estimated with the PTV algorithm, which only  
521considers moving sediment particles. It is similar, however, to the velocities measured by the  
522ADVP in the bin containing the surface of the immobile bed (cf. section "ADVP  
523configuration and data analysis procedures"). The temporal fluctuations of this locally  
524spatially averaged velocity will be shown and discussed in the section "Simultaneous  
525videography".

## 526RESULTS

### 527Signature of the raw signals recorded by the ADVP

528Most commercial ADVP systems only provide as output the quasi-instantaneous Doppler  
529frequencies or velocities sampled at PRF/NPP. The ADVP used in the present investigation  
530also provides the backscattered raw return signals recorded by the receivers,  $I$  and  $Q$ , sampled  
531at PRF. This is a major advantage, as it allows analysing the raw signals for the presence of a  
532footprint of bedload sediment transport. This analysis will be illustrated for the Q795L  
533experiment, where the bed level remained stable during the entire 624 s of continuous  
534measurements.

535 First, the time-averaged magnitude of the backscattered raw return signal,  $I^2 = 0.25$   
536  $(I_1^2 + I_2^2 + I_3^2 + I_4^2)$  is considered (Figure 2). The magnitude of the backscattered signal relates to  
537 the concentration of the sediment particles, because sediment particles backscatter  
538 considerably more acoustic energy than micro air-bubbles in the water column above  
539 (Hurther et al. 2011). The magnitude of the return signal decreases with distance upwards  
540 from the immobile bed level, which complies with the expectation that sediment  
541 concentration decreases with distance from the immobile bed. We hypothesize that the bins  
542 with considerably increased magnitude of the return signal correspond to the layer of rolling  
543 and sliding bedload sediment, and that bins characterized by the base level of acoustic  
544 backscatter magnitude correspond to clear water flow. Bins in between the rolling and sliding  
545 bedload transport layer and the clear water flow layer are assumed to correspond to saltating  
546 bedload.

547 Second, the signature of the time-series of the  $I$  signal is investigated in bins near the  
548 bed. Figure 6 focuses on a 0.2 s time-series sampled at PRF = 1000 Hz in the bin containing  
549 the immobile bed and the three overlaying bins. According to the definition (Equation (2)),  
550 the  $I$  signal produced by a moving acoustic scattering source should fluctuate around a zero  
551 value. Figure 6 clearly shows an offset in the time-averaged value of the  $I$  signal, especially  
552 for bins 57 and 58. This offset is due to imprecision in the analog demodulation of the  
553 measured signal. In order to prevent biased estimates, it is important to remove this offset  
554 from the signal before estimating the Doppler frequency according to Equation (4). The  
555 increase in magnitude of the raw return signal towards the bed observed in Figure 2 can be  
556 recognized in the increasing amplitude of the  $I$  fluctuations towards the bed in Figure 6. The  $I$   
557 signal in bin 55 shows oscillations with a frequency and amplitude that varies in time, as can  
558 be expected for flow velocities in clear water. According to Hurther and Thorne (2011) and  
559 Naqshband et al. (2014b), the zero velocity and highest sediment concentration at the



560 immobile bed surface, estimated within bin 58, should in theory correspond to a constant  $I$   
561 value of high amplitude with negligible variance. Figure 6 shows that the measured amplitude  
562 is not always constant, but that sequences of fluctuating voltage occur. These sequences  
563 represent the intermittent passage of bedload particles that roll and slide on the immobile bed  
564 (cf. section “ADVP configuration and data analysis procedures” and Figure 4).

565

[Figure 6]

566 Third, the power spectral densities of the  $I$  signals simultaneously recorded by the  
567 four receivers are investigated. According to the theory outlined in the introduction, the  
568 frequency of the fluctuating  $I$  signal is proportional to the velocity of the acoustic scatterers.  
569 Hence, the power spectral density of the  $I$  signal represents the turbulent fluctuations of the  
570 velocity of the acoustic scatterers (Traykovski 1998, his appendix A). Figure 7 shows these  
571 power spectral densities in the bins corresponding to the estimated layers of rolling and  
572 sliding bedload, saltating bedload, and clear water. For the bin in clear water, these spectral  
573 densities are near Gaussian, as expected for turbulent velocity fluctuations. The peak value  
574 corresponds to a velocity of about  $0.4 \text{ m s}^{-1}$ , which compares favourably with the time-  
575 averaged velocity estimated using the pulse-pair algorithm (Equation 4, Figure 3b). The  
576 lower and higher values represent the turbulent velocity fluctuations. Interestingly, however,  
577 the power spectral density is left-skewed in the bin that is assumed to correspond to the  
578 rolling and sliding bedload layer, which is more consistent with observations of bedload  
579 particle velocities (Drake et al. 1988; Rennie and Millar 2007; Lajeunesse et al. 2010; Furbish  
580 et al. 2012). In the assumed layer of saltating bedload, the spectral densities look like a  
581 combination of a Gaussian and a left-skewed profile.

582

[Figure 7]

583 Fourth, the signature of the time-series of the velocity is investigated in bins near the  
584bed (Figure 8). Velocity fluctuations in the first two bins of the assumed clear water layer  
585(bins 54 and 55) are similar and represent turbulent coherent structures. The velocity  
586fluctuations in bin 56, corresponding to the assumed layer of saltating bedload, seem to be  
587coherent with the fluctuations in the clear water layer, but the amplitude of the velocities is  
588considerably reduced. The velocities in the assumed layer of rolling and sliding bedload (bin  
58957) show less coherence with the turbulent coherent structures in the clear water above. The  
590velocity is considerably smaller in bin 58 containing the immobile bed surface. The non-zero  
591velocities represent the intermittent passage of bedload particles that roll and slide on the  
592immobile bed (cf. section “ADVP configuration and data analysis procedures” and Figure 4).

593 [Figure 8]

594 A similar analysis of the characteristics of the backscattered raw return signal  $I$  (Figures  
5952, 6, 7) and the time-series of the velocities (Figure 8) has been performed for all  
596experiments. This analysis revealed a clear footprint of the bedload sediment transport in the  
597raw return signals, which indicates that the moving bedload sediment grains are the main  
598scattering sources. Because the ADVP measures the velocity of the scattering sources, this  
599analysis provides a first indication that the velocities measured by the ADVP correspond to  
600the velocities of the moving sediment particles. Moreover, this analysis corroborated the  
601identification based on the profile of the time-averaged velocity (Figure 3b) of the bin  
602containing the immobile-bed surface, the layer of rolling and sliding bedload, and the layer of  
603saltating bedload.

#### 604**Simultaneous ADVP measurements and videography**

605Figure 9 shows the results for the time-averaged velocities in the main series of experiments.  
606All relevant information is provided in Table 2 for the experiments with low acoustic power

607and in Table S1 of the supporting information for the experiments with high acoustic power.  
608The total duration of each experiment has first been divided into periods with quasi-constant  
609conditions. The reference z-level has been taken as the lowest level of the immobile-bed  
610surface during the total duration of each experiment. The rise of the immobile bed level  
611during the passage of a dune in the Q630L experiment, for example, is visible in the shift to  
612right of the measured velocity profiles in Figure 9a. Similarly, the important variations in the  
613immobile bed level due the break up of the armour layer in the Q1000L experiment are  
614clearly visible in Figure 9e.

615 [Figure 9]

616 For each of the periods with quasi-constant conditions, the vertical profile of  
617streamwise velocity measured in water column bins within the sensitivity range of the ADVP  
618(beyond gate 37) fit the log-law very well (Figure 9). However, measured velocities in the  
619near-bed bins was systematically less than expected from the log-law.

620 In the near-bed zone, the bin containing the immobile-bed surface and the layers of  
621rolling and sliding bedload, saltating bedload, and clear water have been identified from the  
622time-averaged velocity profile and the profile of the magnitude of the backscattered raw  
623return signal as described in the section “ADVP configuration and data analysis procedures”.  
624The identification of these different layers was confirmed by the analysis of the backscattered  
625raw return signal  $I$  and the time-series of the velocities as described in the section “Signature  
626of the raw signals recorded by the ADVP”.

627 The gray shaded areas in Figure 9 represent the distribution functions of the sediment  
628velocities based on the PTV treatment of the eleven sequences of videography in each  
629experiment (e.g., periods marked by red lines in Figure 5). The average particle velocity  
630computed from these distribution functions, also indicated in the figure, agrees well with the

631ADVP estimation of the dominant bedload velocity, which occurs at the elevation where the  
632slip velocity is maximum (cf. section “ADVP configuration and data analysis procedures”).  
633The relative and absolute differences between the average particle velocity estimated from  
634ADVP and videography in each experiments are  $21 \% \pm 9\%$  and  $0.0275 \text{ m s}^{-1} \pm 0.0125 \text{ m s}^{-1}$ ,  
635respectively. This absolute difference is much smaller than the velocity variation within one  
636bin of the ADVP measurements (Figure 9).

637 The average bedload velocity in the Q795L experiment is similar to that in the Q630L  
638experiment, which can be attributed to the armouring of the bed. The average bedload  
639velocity in the Q1000L experiment is substantially higher. The highest velocities of bedload  
640particles observed in the video images (highest velocities in the gray distribution functions)  
641were only slightly smaller than the velocity measured with the ADVP at the top of the non-  
642logarithmic flow layer near the bed (Figure 9). This observation supports the hypothesis that  
643these fastest moving particles were saltating bedload particles that had less slip velocity than  
644rolling and sliding bedload particles. The shape of the distribution functions based on the  
645videography (Figure 9) resemble the shape of the power spectral density distributions of the  
646velocities measured with the ADVP in the bedload layer (Figure 7), further suggesting that  
647the latter represent the velocity of the bedload sediment particles.

648 For the three investigated conditions shown in Figure 9, each experiment with low  
649acoustic power was immediately followed by an experiment with high acoustic power (Figure  
6502). The latter corresponds to the standard ADVP configuration for optimal flow  
651measurements in the body of the water column, but may lead to magnitudes of the  
652backscattered raw return signal  $I$  that are frequently out of the recording range of the  
653receivers near the bed. The former corresponds to the ADVP configuration optimized for  
654measurements near the bed. A better resolution of the sediment velocity would be expected  
655with low acoustic power and a better resolution of the flow with high acoustic power.

656Differences between results from experiments with low and high acoustic power were found  
657to be insignificant and within the experimental uncertainty (Figure 9). However, for the Q795  
658experiments, only about 10 % of the raw  $I(t)$  signal had a magnitude outside the receivers'  
659recording range in the bin containing the surface of the immobile bed in the experiment with  
660low acoustic power (Figure 2; Figure 6d), whereas 36% was out-of-range in the experiment  
661with high acoustic power (Figure 2). These results demonstrate the robustness of the pulse-  
662pair algorithm (Equation 4), which provides accurate estimations of the average velocity even  
663in the presence of a non-negligible number of out-of-range values of  $I$  and  $Q$ . An important  
664conclusion from this result is that measurements of the bedload sediment velocities can be  
665performed with the standard configuration of the ADVP.

666

[Figure 10]

667 Figure 10 shows time series of the velocities in the main series of experiments with low  
668acoustic power. It compares the quasi-instantaneous velocities spatially averaged within the  
669ADVP measurement volume estimated with the Optical Flow algorithm to those measured  
670with the ADVP in the bin containing the surface of the immobile bed and the bin just above  
671(Table 2), where the rolling and sliding bedload sediment transport occurs. As explained  
672before, the upper part of the bin containing the surface of the immobile bed is situated in the  
673flow where bedload sediment particles roll and slide on the immobile bed (Figure 4), whence  
674the ADVP measures in that bin a non-zero velocity. As also explained before, both the ADVP  
675measurement in the bin containing the surface of the immobile bed, and the Optical Flow  
676algorithm provide an average sediment velocity that includes areas of zero velocity associated  
677with immobile particles. This explains why they provide velocities that are substantially  
678lower than those estimated with the PTV algorithm, which only considers moving sediment  
679particles in the water column (Figure 9).

680 For the sake of clarity, only two 10 s sequences of videography are shown for each  
681 experiment. In the Q630L and Q795L experiments, both the magnitude and the time series of  
682 the quasi-instantaneous velocities estimated from the videography with the Optical Flow  
683 algorithm agree very well with those measured by the ADV in the bin containing the  
684 immobile-bed surface (Figures 10a and 10b), indicating that most of the bedload sediment  
685 transport occurred in the form of rolling and sliding particles within the bin containing the  
686 immobile-bed surface. This complies with the observation that only partial transport of  
687 sediment occurred in these experiments (Table 1), and that the largest particles moving were  
688 smaller than the ADV's bin size. In the Q1000L experiment, the temporal evolutions of the  
689 velocities estimated from the videography and measured with the ADV are clearly related,  
690 but the velocities estimated with the Optical Flow algorithm are generally smaller than those  
691 measured with the ADV. In this experiment, generalized intense sediment transport occurred  
692 (Table 1), and the largest particles moving were larger than the ADV's bin size. The layer of  
693 rolling and sliding bedload particles was at least two bins thick, and overlaid by a layer of  
694 smaller and faster moving saltating bedload particles of at least three bins thick (Figures 9e  
695 and 9f) The underestimation of the bedload velocities in the Q1000L experiment by the  
696 Optical Flow algorithm is tentatively attributed to the fact that the algorithm only resolves the  
697 velocity of the largest and slowest bedload particles, whereas the ADV resolves the velocity  
698 of all particles.

699 These results are further substantiated by the cross-correlations between the  
700 fluctuations of velocities measured with the ADV in the bin containing the surface of the  
701 immobile bed and estimated with the Optical Flow algorithm. These cross-correlations are  
702 defined as:

$$C = \frac{\overline{u_{ADV} u_{OF}}}{\sqrt{\overline{u_{ADV}^2}} \sqrt{\overline{u_{OF}^2}}} \quad (6)$$

703

704 where the prime denotes the fluctuating component of the velocity time-series and the  
705 overbar denotes time-averaging. The cross-correlation for the Q1000L experiment are  
706 relatively low at  $C=0.22\pm 0.04$ , which complies with the important deviations between the  
707 time-series measured by ADV and Optical Flow (Figure 10c). The cross-correlations for the  
708 Q630L and Q795L experiments are considerably higher at  $C=0.41\pm 0.04$  and  $C=0.74\pm 0.04$ ,  
709 respectively. These values further indicate that the ADV also resolves the details of the  
710 temporal fluctuations of bedload particle velocities.

### 711 Comparison to semi-theoretical formulae based on previous results

712 Figure 11 summarizes results from all experiments, including the second series of  
713 experiments with flow depths of 0.14 m and 0.24 m measured with the standard configuration  
714 of the ADV with high acoustic power, and without simultaneous videography. All relevant  
715 information is provided in tabular form as supporting information. For each of these flow  
716 depths, ten different discharges were tested, ranging from conditions without sediment  
717 transport to conditions with generalized sediment transport. Figure 11 presents the bedload  
718 velocity and layer thicknesses measured with the ADV as a function of the shear velocity  $u_*$ .  
719 In straight uniform open-channel flows, Nezu and Nakagawa (1993) have proposed a semi-  
720 theoretical logarithmic profile for the streamwise velocity, exponential profile for the  
721 turbulent kinetic energy, and linear profile for the streamwise-vertical turbulent shear stress,  
722 which all scale with the shear velocity. Fitting of the measured vertical profiles to these semi-  
723 theoretical similarity solutions provides three estimates of  $u_*$ . The average of these three  
724 estimates is used on the abscissa in Figure 11. Each of the experiments of the second series  
725 was also divided into periods of quasi-constant conditions. Because differences between  
726 different periods were relatively small, only one average result is reported in Figure 11 for  
727 each experiment.

728

[Figure 11]

729 Figure 11a reports the velocity of the bed load particles estimated from the ADVP  
730 measurements. For the main series of experiments, bedload velocity estimated from the  
731 videography with the PTV algorithm is also shown. For  $u_*$  smaller than  $0.02 \text{ m s}^{-1}$ , the bed is  
732 stable and no bedload sediment transport occurs. Note that  $u_{*,cr} = 0.02 \text{ m s}^{-1}$  corresponds to  
733 the critical shear velocity for the initiation of sediment transport for  $d_{50}$  based on the Shields  
734 criterion (Shields 1936). When bedload transport occurs, the bedload velocity increases with  
735 increasing shear velocity, in line with results reported in literature. According to Lajeunesse  
736 et al. (2010, their equations 26 and 27), the average velocity of bedload particles,  $v_{bedload}$ , can  
737 be written as:

$$738 \quad v_{bedload} = a(u_* - u_{*,cr}) + 0.11v_{settling} \quad (7)$$

739 where  $u_*$  and  $u_{*,cr}$  are the shear velocity and the critical shear velocity for the initiation of  
740 bedload transport, respectively, and  $v_{settling}$  is the characteristic settling velocity of the  
741 sediment. As mentioned above, the critical shear velocity for  $d_{50}$  is  $0.02 \text{ m s}^{-1}$ . According to  
742 Brown and Lawler (2003) the settling velocity for  $d_{50}$  is  $0.118 \text{ m s}^{-1}$ . Different values are  
743 reported in literature for the coefficient  $a$ . Based on experimental observations of sediment  
744 moving above a mobile bed, Lajeunesse et al. (2010) reported a value of  $4.4 \pm 0.2$  whereas  
745 Fernandez-Luque and Van Beek (1976) reported a value of  $13.2 \pm 0.6$ . The latter value was  
746 also reported by Abbott and Francis (1977) and Lee and Hsu (1994) for a single grain particle  
747 entrained above a rigid rough bed. The  $a$  value proposed by Lajeunesse et al. (2010) was  
748 based on experiments with sediment diameters of  $d_{50} = 0.00115 \text{ m}$ ,  $0.00224 \text{ m}$  and  $0.0055 \text{ m}$ ,  
749 and Shields parameters in the range from 0.006 to 0.24. Fernandez-Luque and Van Beek  
750 (1976) performed experiments with sediment diameters of  $d_m = 0.0009 \text{ m}$ ,  $0.0018 \text{ m}$ , and  
751  $0.0033 \text{ m}$ , and ratios of the Shields parameter to the critical Shields parameter for the  
752 initiation of motion of 1.1 to 2.7. These experimental conditions are comparable to those in  
753 the experiments reported in the present paper. The bedload velocity according to equation 7



754for both values of  $a = 4.4$  and  $13.2$  envelopes all data from the here reported experiments  
 755(Figure 11a).

756 Figure 11b reports the thickness of the layer of rolling and sliding bedload (defined in  
 757the section “ADVP configuration and data analysis procedures“ and indicated in Figure 9)  
 758estimated from the ADVP measurements, which increases as expected with increasing shear  
 759velocity. The resolution of the bedload layer thickness is obviously limited by the size of the  
 760ADVP measuring bins of  $0.004$  m. The estimated bedload layer thickness increases from  
 761about 1 bin ( $0.004$  m) at low transport to about 2 bins at high transport ( $0.008$  m). Based on  
 762the solution of the equations of motion for a solitary particle, van Rijn (1984, Equation 10)  
 763proposed the following equation for the bedload layer thickness:

$$764 \quad \text{thickness} = 0.3 d \left[ d \frac{(\rho_s/\rho - 1) g}{\nu^2} \right]^{1/3} (u_*^2/u_{*c}^2 - 1)^{1/2} \quad (8)$$

765where  $d$  is a characteristic diameter of the bedload sediments, taken as  $d_{50}$  by van Rijn (1984),  
 766 $\rho_s$  and  $\rho$  are the densities of the sediment and the water, respectively,  $g$  is the gravitational  
 767acceleration and  $\nu$  is the kinematic viscosity of the water. Van Rijn (1984) calibrated this  
 768equation based on experiments with a uniform sediment diameter of  $d = 0.0018$  m and a shear  
 769velocity of  $0.04$  m s<sup>-1</sup>. These parameters are in the same range as in the experiments reported  
 770herein. All data on the bedload layer thickness estimated from the ADVP measurements in the  
 771present experiments are constrained by two curves, corresponding to predictions based on  
 772Equation 8 for bedload sediment diameters of  $d = d_{50} = 0.0008$  m and  $d = 0.0015$  m. Hence,  
 773the ADVP estimates of the bedload layer thickness comply with the equation and underlying  
 774experiments of van Rijn (1984).

775 It is noteworthy that results for the velocities and thicknesses are quite similar for  
 776experiments Q630 and Q795 in the main series of experiments, and strongly increase from

777Q795 to Q1000. This behaviour can be attributed to the gradual formation of the armour layer  
778in Q630, which limits bedload transport in Q795, and the break up of the armour layer in  
779Q1000.

## 780**Comparison of standard ADVP configuration and ADVP configuration optimized for** 781**bedload measurements**

782 Both for the sediment velocity in the bedload layer, and the thickness of the dominant  
783bedload layer, results of the experiments with a flow depth of 0.24 m in the second series  
784with standard ADVP configuration (Table S2 of the supporting information) agree well with  
785results in the main series with ADVP configuration optimized for bedload measurements  
786(Table 2). Experiments with similar hydraulic conditions are compared (Q630L vs. Q605H,  
787Q795L vs. Q794H and Q795H, and Q1000L vs. Q897H). The relative and absolute  
788differences between the average particle velocity estimated with standard and optimized  
789ADVP configurations are  $20 \% \pm 8\%$  and  $0.032 \text{ m s}^{-1} \pm 0.025 \text{ m s}^{-1}$ , respectively. This  
790absolute difference is much smaller than the velocity variation within one bin (Figure 9).  
791Both ADVP configurations provided identical estimations of the thickness of the dominant  
792bedload layer. This confirms that the standard ADVP configuration provides reliable  
793estimations of the bedload characteristics. It is noteworthy that results for the velocities and  
794thicknesses are quite similar for experiments Q630 and Q795 in the main series of  
795experiments, and strongly increase from Q795 to Q1000. This behaviour can be attributed to  
796the gradual formation of the armour layer in Q630, which limits bedload transport in Q795,  
797and the break up of the armour layer in Q1000.

## 798**DISCUSSION AND CONCLUSIONS**

799 Previous experiments have indicated that near-bed velocities can deviate from the  
800logarithmic profile due to beam geometry effects, i.e. contamination of the near-bed bins by

801high intensity scatter from the immobile bed (Hay et al. 20121), and due to the presence of  
802bedload sediment transport (Naqshband et al. 2014b). The ellipses of equal acoustic travel  
803time for the near-bed bins have been drawn in Figures 1a and 1b for the ADVP configurations  
804adopted in the here reported experiments. These purely geometrical considerations indicate a  
805potential contamination zone due to beam geometry effects of approximately 0.01 m. This is  
806a conservative estimation, however, which does not take into account that the acoustic power  
807is maximal in the centre of the insonified beam and decays in a Gaussian way towards its  
808edges. In all experiments without sediment transport reported in this paper, the ADVP  
809resolved the law of the wall logarithmic velocity profile, including in the first bin above the  
810immobile bed (Figure 3a). This indicates that the contamination zone due to beam geometry  
811effects is smaller than 0.004 m. On the contrary, in all experiments with bedload sediment  
812transport reported in this paper, velocities in the near-bed region where bedload sediment  
813transport occurs were systematically smaller than expected from the logarithmic law of the  
814wall (Figure 3a,b and Figure 9), similar to observations by Naqshband et al. (2014b). The  
815deviating velocities occurred in a layer of approximately 0.004 m to 0.02 m from the  
816immobile bed (Figure 3 and Figure 9). These observations indicate that the velocity deficit in  
817the near-bed region is essentially related to the transport of bedload in the reported  
818experiments.

819 Results from all three strategies corroborate the main hypothesis of the present paper  
820that the ADVP does measure sediment velocities, also in the near-bed layer where bedload  
821transport occurs. First, the backscattered raw return signals  $I(t)$  recorded by the ADVP's  
822receivers reveal a clear footprint of the bedload sediment particles. The magnitude of  $I(t)$  in  
823the bins where bedload sediment transport occurs clearly exceeds that of bins above in the  
824clear water flow (Figures 2 and 6) , which is due to the fact that sediment particles  
825backscatter considerably more acoustic energy than micro air-bubbles in the clear water

826(Hurther et al. 2011). Thus, the sediment particles are the main scattering sources in the  
827insonified water column, and it is therefore their velocity that is measured by the ADVP.  
828Spectra of the  $I(t)$  signals are near-Gaussian in the clear water and left-skewed near the bed  
829where bedload sediment transport occurs. The latter distribution is characteristic for bedload  
830sediment transport (Figure 7), in agreement with recent findings (Drake et al. 1988, Rennie  
831and Millar 2007, Lajeunesse et al. 2010, Furbish et al. 2012). Second, results from the  
832simultaneous videography of the bedload sediment transport are in good agreement with  
833ADVP results. Time-averaged velocities measured with the ADVP in the layer of rolling and  
834sliding bedload transport agree well with those estimated from the digital video images of the  
835moving sediment with a particle tracking algorithm (Figure 9). Moreover, velocity time series  
836(mean and fluctuating components) measured with the ADVP in the bin containing the  
837immobile-bed surface agree well with the time series of the average bed velocity estimated  
838with the Optical Flow algorithm (Figure 10). Third, ADVP based estimates of the bedload  
839velocities and thickness of the bedload layer are in agreement with semi-theoretical formulae  
840based on previous experiments proposed by Lajeunesse et al. (2010) and van Rijn (1984),  
841respectively, for a broad range of hydraulic conditions (Figure 11).

842 The ADVP configuration optimized for bedload measurements only marginally  
843performs better than the standard configuration for flow measurements, which also provides  
844satisfactory estimates of the sediment velocity and transport layer thickness.

845 These findings corroborate the hypothesis of Hurther et al. (2011) and Naqshband et al.  
846(2014b) that the ADVP can measure the time-averaged velocity of bedload particles, and the  
847hypothesis of Naqshband et al. (2014a) that it also measures the temporal fluctuations of the  
848particle velocities. The shear velocities in the reported experiments were comparable to those  
849in the experiments of Naqshband et al. (2014a,b), but their sediment size was about 10 times  
850smaller, leading to Shields numbers that were about 10 times higher, and resulting in more

851intense bedload transport and significant suspended load transport. Both the present study and  
852Naqshband et al. (2014a,b) used a similar ADVP with carrier frequency  $f_0 = 1$  MHz, resulting  
853in a wavelength of the emitted acoustic pulses of about  $\lambda = c/f_0 = 0.0015$  m. The sediment  
854particles were smaller than this wavelength in Naqshband's experiment, leading to Rayleigh  
855backscattering of the acoustic pulse. The particles were larger than this wavelength in our  
856experiments, leading to geometric scattering. These results indicate that the ADVP is able to  
857measure turbulent bedload velocities and the bedload layer thickness for a broad range of  
858sediment diameters and different regimes of scattering.

859        These results confirm that ACVPs (Hurther et al. 2011), which integrate an ADVP with  
860an Acoustic Backscatter System (ABS), are able to measure turbulent sediment fluxes  
861according to Equation (1). The ABS ability to measure sediment concentration in the entire  
862water column, including the bedload layer, has been demonstrated (Naqshband et al. 2014b).  
863When sediment transport occurs, the ADVP provides unbiased measurements of the sediment  
864velocity  $u_s$ , even in the near-bed layer where bedload sediment transport occurs. Velocities of  
865bedload sediment will be smaller than velocities of the surrounding water, whereas velocities  
866of suspended load sediment will be about equal to velocities of the surrounding water. When  
867no sediment transport occurs, the ADVP measures the velocity of the clear water flow. The  
868presence or non-presence of sediment in the water column is indicated by the ABS  
869measurements of concentration. The position of the surface of the immobile bed can  
870independently be estimated from the ADVP measurements as in the present paper, and from  
871the ABS measurements as done by Hurther et al. (2011).

872        The present paper has proposed straightforward criteria based on the shape of the  
873velocity profile to identify the layers of rolling and sliding bedload, saltating bedload, and  
874suspended load or clear water (Figures 3 and 9). As a complementary approach, Hurther et al.  
875(2011) identified the suspended load layer based on characteristics of the concentration

876 profile measured with ABS, and defined the bedload layer as the intermediate layer between  
877 the immobile bed and the suspended load layer. The identification of these different layers is  
878 mainly important for comparison to commonly used formulae for bedload and suspended  
879 load transport. It is of minor importance in practical applications, however, because the river  
880 morphology is mainly determined by the total sediment flux estimated according to Equation  
881 (1).

882       The reported ADVP bedload results are sensitive to vertical resolution of the ADVP  
883 system. The bin size in the reported experiments was 0.004 m, which is the minimum bin size  
884 of the applied ADVP. Uncertainty in the determination of the levels of the immobile-bed  
885 surface, the layer of rolling and sliding bedload, and the layer of saltating bedload is about  
886 half a bin. In this case, the uncertainty of about 0.002 m in the vertical elevation is  
887 comparable to the mean diameter of the sediment ( $d_m = 0.0023$  m). Moreover, the near-bed  
888 velocities change considerably within one bin (cf. Figure 9). Using interpolated estimates of  
889 these levels corresponding to half a bin (included in tabular form in Table 2 for the main  
890 series of experiments with low acoustic power and in the supporting information for the other  
891 experiments) considerably reduces discrepancies between velocities measured with ADVP  
892 and estimated from the digital video images, as well as the scatter in Figure 11 (which is not  
893 based on half-bin interpolations). These observations highlight the importance of an optimal  
894 choice of the ADVP parameters, and especially the bin size, which should be small compared  
895 to the thickness of the bedload layer. Naqshband et al. (2014a) adopted a bin size of 0.003 m  
896 in their investigation of sediment fluxes over equilibrium dunes, which was the minimum bin  
897 size of their ADVP, whereas the broadband multifrequency ADVP developed by Hay et al.  
898 (2012 a,b,c) is capable of a bin size of 0.0009 m.

899       A major advantage of ADVP's is their versatility, and the possibility to optimize their  
900 configuration for particular applications. The bin size, for example, is constrained by the

$$V_{\max} = PRF \frac{C}{4 f_0}$$

901wavelength of the emitted acoustic pulse,  $\lambda = c/f_0$ , and can be reduced by increasing the  
 902carrier frequency  $f_0$ , bearing in mind that the maximum unambiguously measureable velocity  
 903is inversely proportional to  $f_0$  (Pinkel 1980).

904 (9)

905PRF is also related to the maximum profiling range  $D_{max}$ , which represents the longest travel  
 906path of the acoustic pulse between emitter and receiver in the measured water column:

$$907 \quad D_{max} = \frac{c}{2PRF} \quad (10)$$

908In the here applied ADVP configuration,  $D_{max}$  is slightly larger than twice the maximum  
 909height of the investigated water column. Combining the constraints in equations (9) and (10)  
 910leads to the well-known range-velocity ambiguity relations in pulse-coherent Doppler  
 911systems (Pinkel 1980):

$$912 \quad 4V_{max} \frac{f_0}{c} < PRF < \frac{c}{D_{max}} \quad \text{and} \quad V_{max} D_{max} = \frac{c^2}{4f_0} \quad (11)$$

913These relations show that pulse coherent systems must trade off the bin size, maximum  
 914observable velocities and maximum range of profiling, depending on operating frequency. If  
 915operating frequency is increased to reduce bin size, then PRF could be increased to maintain  
 916the same maximum measurable velocity (Equation 9). However, the profiling range would be  
 917reduced (Equation 10). This is not a major drawback in sediment transport applications,  
 918where the main region of interest is located in the vicinity of the bed. The ADVP acoustic  
 919operating frequency can be optimized based on the transport velocity and thickness of the  
 920bedload layer as predicted, for example, by means of Equations (7) and (8). It is worth noting  
 921that these principles underlying the optimal choice of the operating frequency, PRF and  
 922profiling range of the ADVP configuration are identical in measurements of turbulent flow

923and measurements of sediment transport, although high sediment concentration may impede  
924use of higher operating frequencies due to increased acoustic attenuation.

925 The ADVP and the data treatment procedure outlined in the present paper can be  
926applied for sediment transport investigations in the laboratory and in the field. The standard  
927set-up for field investigations would involve placing the ADVP transducers immersed in the  
928flowing water about  $O(1\text{m})$  above the surface of the immobile bed, in order to focus on the  
929near-bed region where sediment transport occurs. The ADVP could be mounted on a standard  
930platform as commonly used in field investigations in river and coastal applications. Such a  
931set-up would also be appropriate to validate the in-field ADCP technique for measuring the  
932apparent bedload velocity developed by Rennie et al. (2002), Rennie and Church (2010) and  
933Williams et al. (2015).

934 The demonstrated capability of the ADCP (which integrate ADVP and ABS) to measure  
935sediment fluxes, including bedload fluxes has important implications, because no reliable  
936technique is at present available to measure sediment fluxes. The results broaden the  
937application range of ADCP in laboratory and field investigations, and should lead to  
938enhanced insight in the dynamics of sediment transport and morphodynamic processes.  
939Follow-up studies are required in bespoke laboratory settings with an optimized simultaneous  
940deployment of ADVP and high-speed videography, and possibly complementary physical  
941sampling, in order to estimate the accuracy and uncertainty in the sediment velocity  
942measurements, and to delimit the application range of the ADVP technique.

943

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## 952 REFERENCES

953 Abbott, J., and J. Francis (1977), Saltation and suspension trajectories of solid grains in a  
954 water stream, *Philos. Trans. R. Soc. London A*, 284, 225–254.

955 Ancy, C., and J. Heyman (2014), A microstructural approach to bed load transport: Mean  
956 behaviour and fluctuations of particle transport rates, *J. Fluid Mech.*, 744, 129-168.

957 Beutelspacher, A., and U. Rosenbaum (1998), *Projective Geometry: From Foundations to*  
958 *Applications*, Cambridge Univ. Press, Cambridge, UK, ISBN 0-521-48364-6.

959 Blanckaert, K. (2010), Topographic steering, flow recirculation, velocity redistribution,  
960 and bed topography in sharp meander bends, *Water Resour. Res.*, 46, W09506,  
961 doi:10.1029/2009WR008303.

962 Blanckaert, K., and H. J. de Vriend (2004), Secondary flow in sharp open channel bends, *J.*  
963 *Fluid Mech.*, 498, 353–380.

964 Blanckaert, K., and U. Lemmin (2006), Means of noise reduction in acoustic turbulence  
965 measurements, *J. Hydraulic Res.*, 44(1), 3-17.

966 Bose, S. K., and S. Dey (2013), Sediment entrainment probability and threshold of sediment  
967 suspension: exponential-based approach, *J. Hydr. Eng.*, 139(10), 1099-1106.

968Bricault, M. (2006), Rétrodiffusion acoustique par une suspension en milieu turbulent:  
969 application à la mesure de concentration pour l'étude des processus hydrosédimentaires.  
970 PhD thesis, Grenoble Institut National Polytechnique.

971Brown, P. P., and D. F. Lawler (2003), Sphere drag and settling velocity revisited. *J.*  
972 *Environmental Eng.*, 129(3), 222-231.

973Cellino, M., and W. H. Graf (2000), Experiments on suspension flow in open channels with  
974 bedforms, *J. Hydraul. Res.*, 38, 289–298.

975Church, M. (2006), Bed material transport and the morphology of alluvial river channels,  
976 *Ann. Rev. Earth and Planetary Sciences*, 34 , 325-354.

977Crawford, A. M., and A. E. Hay (1993), Determining Suspended Sand Size and  
978 Concentration from Multifrequency Acoustic Backscatter, *J. Acoustical Soc. Am.*, 94(6),  
979 3312-3324.

980Drake, T. G., Shreve, R. L., Dietrich, W. E., Whiting, P. J., and L. B. Leopold (1988), Bedload  
981 transport of fine gravel observed by motion-picture photography, *J. Fluid Mech.*, 192, 193-  
982 217.

983Ferguson, R. I., Ashmore, P. E., Ashworth, P. J., Paola, C., and K. L. Prestegard (1992),  
984 Measurements in a braided river chute and lobe 1. flow pattern, sediment transport, and  
985 channel change, *Water Resour. Res.*, 28(7), 1877-1886.

986Fernandez-Luque, R., and R. Van Beek (1976), Erosion and transport of bed-load sediment,  
987 *J. Hydraul. Res.*, 14, 127–144.

988Frey, P., Ducottet, C., and J. Jay (2003), Fluctuations of bed load solid discharge and grain  
989 size distribution on steep slopes with image analysis, *Exp. Fluids*, 35 (6), 589{597.

990 Furbish, D. J., Roseberry, J. C., and M. W. Schmeeckle (2012), A probabilistic description of  
991 the bed load sediment flux: 3. The particle velocity distribution and the diffusive flux, *J.*  
992 *Geophys. Res.: Earth Surf.*, 117(3), F03033.

993 Gaeuman, D., and R. B. Jacobson (2006), Acoustic bed velocity and bed load dynamics in a  
994 large sand bed river, *J. Geophys. Res.: Earth Surf.*, 111(2), F02005.

995 Guerrero, M., Rütger, N., Szupiany, R., Haun, S., Baranya, S., and F. Latosinski (2016), The  
996 Acoustic Properties of Suspended Sediment in Large Rivers: Consequences on ADCP  
997 Methods Applicability, *Water-MDPI*, 8(1), Article number 13.

998 Guerrero, M., Szupiany, R. N., and M. L. Amsler (2011), Comparison of acoustic  
999 backscattering techniques for suspended sediments investigations, *Flow Meas. Instrum.*,  
1000 22, 392-401.

1001 Guerrero, M., Szupiany, R. N., and F. Latosinski (2013), Multi-frequency acoustics for  
1002 suspended sediment studies: An application in the Parana River, *J. Hydraul. Res.*, 51, 696-  
1003 707.

1004 Hay, A. E., Zedel, L., Cheel, R., and J. Dillon (2012a), Observations of the vertical structure  
1005 of turbulent oscillatory boundary layers above fixed roughness beds using a prototype  
1006 wideband coherent Doppler profiler: 1. The oscillatory component of the flow, *J.*  
1007 *Geophys. Res.: Oceans*, 117(3), C03005, doi:10.1029/2011JC007113.

1008 Hay, A. E., Zedel, L., Cheel, R., and J. Dillon (2012b), Observations of the vertical structure  
1009 of turbulent oscillatory boundary layers above fixed roughness using a prototype wideband  
1010 coherent Doppler profiler: 2. Turbulence and stress, *J. Geophys. Res.: Oceans*, 117(3),  
1011 C03006, doi:10.1029/2011JC007114.

1012 Hay, A. E., Zedel, L., Cheel, R., and J. Dillon (2012c), On the vertical and temporal structure  
1013 of flow and stress within the turbulent oscillatory boundary layer above evolving sand  
1014 ripples, *Cont. Shelf Res.*, 46(1), 31-49.

1015 Heitz, D., Héas, P., Mémin, E., and, J. Carlier (2008), Dynamic consistent correlation-  
1016 variational approach for robust optical flow estimation, *Exp. Fluids*, 45(4), 595-608.

1017 Heyman, J. (2014), A study of the spatio-temporal behaviour of bed load transport rate  
1018 fluctuations. PhD thesis no 6256, EPFL, Lausanne, Switzerland.

1019 Heyman, J., Mettra, F., Ma, H. B., and C. Ancey (2013), Statistics of bedload transport over  
1020 steep slopes: Separation of time scales and collective motion, *Geophys. Res. Lett.*, 40 (1),  
1021 128-133.

1022 Horn, B. K. P., and B. G. Schunck (1981), Determining optical flow. *Artificial Intelligence*,  
1023 17(1-3), August 1981 185-203, ISSN 0004-3702, [http://dx.doi.org/10.1016/0004-](http://dx.doi.org/10.1016/0004-3702(81)90024-2)  
1024 [3702\(81\)90024-2](http://dx.doi.org/10.1016/0004-3702(81)90024-2).

1025 Hurther, D. (2001), 3-D acoustic Doppler velocimetry and turbulence in open-channel flow.  
1026 PhD thesis no 2396, EPFL, Lausanne, Switzerland.

1027 Hurther, D., and U. Lemmin (1998), A constant beamwidth transducer for three-dimensional  
1028 Doppler profile measurements in open channel flow, *Meas. Sc. Techn.*, 9(10), 1706-1714.

1029 Hurther, D., and U. Lemmin (2001), A correction method for turbulence measurements with a  
1030 3D acoustic Doppler velocity profiler, *J. Atm. Ocean. Techn.*, 18(3), 446-458.

1031 Hurther, D., and U. Lemmin (2008), Improved turbulence profiling with field-adapted  
1032 acoustic Doppler velocimeters using a bifrequency Doppler noise suppression method, *J.*  
1033 *Atm. Ocean. Techn.*, 25(3), 452-463.

1034 Hurther, D., and P. D. Thorne (2011), Suspension and near-bed load sediment transport  
1035 processes above a migrating, sand-rippled bed under shoaling waves, *J. Geophys. Res.:*  
1036 *Oceans*, 116(7), C07001.

1037 Hurther, D., Thorne, P. D., Bricault, M., Lemmin, U., and J. M. Barnoud (2011), A multi-  
1038 frequency Acoustic Concentration and Velocity Profiler (ACVP) for boundary layer  
1039 measurements of fine-scale flow and sediment transport processes, *Coastal Engineering*,  
1040 58(7), 594-605.

1041 Klar, M., Jehle, M., Jähne, B., Detert, M., Jirka, G. H., Köhler, H.-J., and T. Wenka (2004),  
1042 Simultaneous 3-D PTV and micro-pressure sensor equipment for flow analysis in a  
1043 subsurface gravel layer. *Proc. River Flow 2004*, 703-712. Eds. Greco, Carravetta, and  
1044 Della Morte, Taylor & Francis Group, London.

1045 Lajeunesse, E., Malverti, L., and F. Charru (2010), Bed load transport in turbulent flow at the  
1046 grain scale: Experiments and modeling, *J. Geophys. Res.: Earth Surf.*, 115(4), F04001.

1047 Latosinski, F., Szupiany, R. N., García, C. M., Guerrero, M., and M. L. Amsler (2014),  
1048 Estimation of Concentration and Load of Suspended Sediment in a Large River by Means  
1049 of Doppler Technology, *J. Hydraul. Eng.*, 140(7), Article number 04014023.

1050 Lee, H.-Y., and I.-S. Hsu (1994), Investigation of saltating particle motions. *J. Hydraul. Eng.*,  
1051 120(7), 831–845.

1052 Leite Ribeiro, M., Blanckaert, K., Roy, A. G., and A. J. Schleiss (2012), Flow and sediment  
1053 dynamics in channel confluences, *J. Geophys. Res.: Earth Surf.*, 117(1), F01035,  
1054 doi:10.1029/2011JF002171.

1055 Lemmin, U., and T. Rolland (1997), Acoustic velocity profiler for laboratory and field  
1056 studies, *J. Hydr. Eng.*, 123(12), 1089–1098.

1057Lhermitte, R., and R. Serafin (1984), Pulse-to-pulse coherent Doppler sonar signal processing  
1058 techniques, *J. Atm. Ocean. Tech.*, 1(4), 293-308.

1059Lucas, B. D., and T. Kanade (1981), An Iterative Image Registration Technique with an  
1060 Application to Stereo Vision, *Proc. of 7<sup>th</sup> Int. Joint Conf. on Artificial Intelligence*,  
1061 Vancouver, Canada, 674–679.

1062Martin, R. L., Jerolmack, D. J., and R. Schumer (2012), The physical basis for anomalous  
1063 diffusion in bed load transport, *J. Geophys. Res.: Earth Surf.*, 117(1), F01018.

1064Mettra, F. (2014), Morphodynamic mechanisms in steep channels: from local processes to  
1065 large-scale evolution. PhD thesis no 6065, EPFL, Lausanne, Switzerland.

1066Miller, K. S., and M. M. Rochwarger (1972), Covariance approach to spectral moment  
1067 estimation, *IEEE Trans. Inform. Theory*, 18(5), 588-596.

1068Moore, S. A., Le Coz, J., Hurther, D., and A. Paquier (2013), Using multi-frequency acoustic  
1069 attenuation to monitor grain size and concentration of suspended sediment in rivers, *J.*  
1070 *Acoust. Soc. Am.*, 133(4), 1959-1970.

1071Mulhoffer L. (1933), Untersuchungen über der Schwebstoff und Geschiebeführung des Inn  
1072 nächst Kirchbichl, Tirol [Investigations into suspended load and bedload of the River Inn,  
1073 near Kirchbichl, Tirol], *Wasserwirtschaft*, Heft 1-6.

1074Muste, M., Yu, K., Fujita, I., and R. Ettema (2009), Two-phase flow insights into open-  
1075 channel flows with suspended particles of different densities, *Env. Fluid Mech.*, 9(2), 161-  
1076 186.

1077Naqshband, S., Ribberink, J. S., Hurther, D., Barraud P. A., and S. J. M. H. Hulscher (2014a),  
1078 Experimental evidence for turbulent sediment flux constituting a large portion of the total  
1079 sediment flux along migrating sand dunes, *Geophys. Res. Lett.*, 41(24), 8870-8878,  
1080 doi:10.1002/2014GL062322.

1081Naqshband, S., Ribberink, J. S., Hurther, D., and S. J. M. H. Hulscher (2014b), Bed load and  
1082 suspended load contributions to migrating sand dunes in equilibrium, *J. Geophys. Res.:*  
1083 *Earth Surf.*, 119(5), 1043–1063, doi:10.1002/2013JF003043.

1084Nezu, I., and H. Nakagawa (1993), *Turbulence in Open Channel Flows*, 281 pp., A. A.  
1085 Balkema, Rotterdam, Netherlands.

1086Nino, Y., and M. H. Garcia, M. H. (1996), Experiments on particle-turbulence interactions in  
1087 the near-wall region of an open channel flow: Implications for sediment transport, *J. Fluid*  
1088 *Mech.*, 326, 285-319.

1089Pinkel, R. (1980), Acoustic Doppler techniques, in *Air–Sea Interaction Instruments and*  
1090 *Methods*, edited by F. Dobson et al., pp. 171–199, New York: Plenum Press.

1091Radice, A., Malavasi, S., and F. Ballio (2006), Solid transport measurements through image  
1092 processing, *Exp. Fluids*, 41(5), 721-734.

1093Rennie, C. D., and M. Church (2010), Mapping spatial distributions and uncertainty of water  
1094 and sediment flux in a large gravel bed river reach using an acoustic Doppler current  
1095 profiler, *J. Geophys. Res.: Earth Surf.*, 115(3), F03035.

1096Rennie, C. D., and R. G. Millar (2007), Deconvolution technique to separate signal from  
1097 noise in gravel bedload velocity data, *J. Hydraulic Eng.*, 133(8), 845-856.

1098Rennie, C. D., Millar, R. G., and M. A. Church (2002), Measurement of bed load velocity  
1099 using an acoustic Doppler current profiler, *J. Hydraulic Eng.*, 128(5), 473-483.

1100Rennie, C. D., and P. V. Villard (2004), Site specificity of bed load measurement using an  
1101 acoustic Doppler current profiler, *J. Geophys. Res.: Earth Surf.*, 109(F3), F03003.

1102Rolland, T., and U. Lemmin (1997), A Two-component Acoustic Velocity Profiler for Use in  
1103 Turbulent Open-channel Flow, *J. Hydraul. Res.*, 35(4), 545–561.

1104Rogers, S. S., Waigh, T. A., Zhao, X., and J. R. Lu (2007), Precise particle tracking against a  
1105 complicated background: polynomial fitting with Gaussian weight, *Phys. Biol.*, 4(3), 220-  
1106 227.

1107Roseberry, J. C., Schmeeckle, M. W., and D. J. Furbish (2012), A probabilistic description of  
1108 the bed load sediment flux: 2. Particle activity and motions, *J. Geophys. Res.: Earth Surf.*,  
1109 117(3), F03032.

1110Ruhnau, P., Kohlberger, T., Schnörr, C., and H. Nobach (2005), Variational optical flow  
1111 estimation for particle image velocimetry, *Exp. Fluids*, 38(1), 21-32.

1112Seizilles, G., Lajeunesse, E., Devauchelle, O., and M. Bak (2014), Cross-stream diffusion in  
1113 bedload transport, *Phys. Fluids*, 26(1), 013302.

1114Shen, C., and U. Lemmin (1999), Application of an acoustic particle flux profiler in particle-  
1115 laden open-channel flow, *J. Hydraulic Res.*, 37(3), 407-419.

1116Shields, A. (1936), Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf  
1117 die Geschiebebewegung [Application of similarity mechanics and turbulence research on  
1118 shear flow]. Mitteilungen der Preußischen Versuchsanstalt für Wasserbau (in German) 26.  
1119 Berlin: Preußische Versuchsanstalt für Wasserbau.

1120Singh, A., Fienberg, K., Jerolmack, D. J., Marr, J., and E. Foufoula-Georgiou (2009),  
1121 Experimental evidence for statistical scaling and intermittency in sediment transport rates,  
1122 *J. Geophys. Res.: Earth Surf.*, 114(1),F01025.

1123Smyth, C., Hay, A. E., and L. Zedel (2002), Coherent Doppler Profiler measurements of near-  
1124 bed suspended sediment fluxes and the influence of bed forms, *J. Geophys. Res.: Oceans*,  
1125 107(C8), 19-1 - 19-20, doi: 10.1029/2000JC000760.



1126 Spies, H., Beringer O., Gröning, H., and H. Haussecker (1999), Analyzing particle  
1127 movements at soil interfaces, in *Handbook on Computer Vision and Applications*, edited  
1128 by B. Jähne et al., vol 3, 699-718, Academic Press.

1129 Stanton, T. P., and E. B. Thornton (1999), Sediment fluxes above a mobile sandy bed in the  
1130 nearshore, *Coastal Sediments '99, Volume One, Proceedings of the 4th International*  
1131 *Symposium on Coastal Engineering and Science of Coastal Sediment Processes*, 241-252.

1132 Stanton, T. P. (2001), Bistatic Doppler velocity and sediment profiler device for measuring  
1133 sediment concentration, estimates profile of mass flux from the product of mass  
1134 concentration and three component velocity vector, Us Sec of Navy. Patent number  
1135 US6262942-B1.

1136 Thorne, P. D., and D. M. Hanes (2002), A review of acoustic measurement of small scale  
1137 sediment processes, *Cont. Shelf Res.*, 22, 603-632.

1138 Thorne, P. D., and P. J. Hardcastle (1997), Acoustic measurements of suspended sediments in  
1139 turbulent currents and comparison with in-situ samples, *J. Acoust. Soc. Am.*, 101(5), 2603-  
1140 2614.

1141 Thorne, P. D., Hardcastle, P. J., and P. S. Bell (1998), Application of acoustics for measuring  
1142 nearbed sediment processes: An integrated approach, *Oceans'98 - Conference*  
1143 *Proceedings*, Vols 1-3, 438-441.

1144 Thorne, P. D., and D. Hurther (2014), An overview on the use of backscattered sound for  
1145 measuring suspended particle size and concentration profiles in non-cohesive inorganic  
1146 sediment transport studies, *Cont. Shelf Res.*, 73, 97-118.

1147 Thorne, P. D., Hurther, D., and B. D. Moate (2011), Acoustic inversions for measuring  
1148 boundary layer suspended sediment processes, *J. Acoust. Soc. Am.*, 130(3), 1188-1200.

1149Traykovski, P. (1998), Observations and modeling of sand transport in a wave dominated  
1150 environment, PhD thesis, Massachusetts Institute of Technology and Woods Hole  
1151 Oceanographic Institution.

1152van Rijn, L. C. (1984), Sediment transport. Part I: bed load transport, *J. Hydraulic Eng.*,  
1153 110(10), 1431-1456.

1154Williams, R. D., Rennie, C. D., Brasington, J., Hicks, D. M., and D. Vericat (2015), Linking  
1155 the spatial distribution of bed load transport to morphological change during high-flow  
1156 events in a shallow braided river, *J. Geophys. Res.: Earth Surf.*, 120(3), 604-622.

1157Wilson, G. W. , and A. E. Hay (2015), Acoustic backscatter inversion for suspended sediment  
1158 concentration and size: A new approach using statistical inverse theory, *Continental Shelf*  
1159 *Research*, 106, 130-149.

1160Wilson, G. W. , and A. E. Hay (2015), Measuring two-phase particle flux with a multi-  
1161 frequency acoustic Doppler profiler, *Journal of the Acoustical Society of America*, 138(6),  
1162 3811-3819.

1163Wright, S. A., Topping, D. T., and C. A. Williams (2010), Discriminating silt and clay from  
1164 suspended sand in rivers using side-looking profilers. In *Proceedings of the 2nd Joint*  
1165 *Federal Interagency Sedimentation Conference*, Las Vegas, NV, USA, 27 June-1 July 2010.

1166Zedel, L., and A. E. Hay (2002), A three-component bistatic coherent Doppler velocity  
1167 profiler: Error sensitivity and system accuracy, *IEEE J. Ocean. Eng.*, 27(3), 717-725.

1168Zedel, L., Hay, A. E., Cabrera, R., and A. Lohrmann (1996), Performance of a single-beam  
1169 pulse-to-pulse coherent Doppler profiler, *IEEE J. Ocean. Eng.*, 21(3), 290-297.

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## Figure Captions

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1173**Figure 1:** Acoustic Doppler Velocity Profiler (ADVP) and digital video camera. The ADVP  
1174consists of a central beam emitter surrounded by four receivers; only two receivers are shown  
1175in the Figure. Theinsonified water column is divided in bins. The fan-beam receivers are  
1176sensitive in a field with a wide opening angle, with maximum sensitivity along the receiver  
1177axis. The red arcs define the ellipses of equal acoustic path travel time between the send and  
1178receive transducers for the bed bin (bottom arc) and the first bin above the bed (top arc). (a)  
1179Standard ADVP configuration optimized for flow measurements in the body of the water  
1180column. The transducers are in a water-filled box that is separated from the flowing water by  
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1182and the receiver axis is focused in the body of the water column. (b) ADVP configuration  
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1184The fan-beam receivers only cover the lower half of the water column, and the receiver axis  
1185is focused on the bed level. (c) Simultaneous deployment of the ADVP optimized for bedload  
1186measurements and a digital video camera focused on the same near-bed sample volume.

1187

1188**Figure 2:** Time-averaged magnitude of the backscattered raw return signal recorded by the  
1189receive transducers,  $I^2$  [ $V^2$ ], for the Q795L experiment with low acoustic power (blue, x) and  
1190the Q795H experiment with high acoustic power (red, o). The configuration with high  
1191acoustic power optimizes the signal-to-noise ratio in the water column but provides a  
1192magnitude of the backscattered signal that is frequently outside the recording range of the  
1193receivers in the bedload layer. The configuration with low acoustic power provides a  
1194backscattered signal that remains within the recording range of the receivers in the bedload  
1195layer. The vertical axis to the left is the bin number, which increases with distance from the  
1196ADVP. The vertical axis to the right is the distance above the surface of the immobile bed.  
1197The full black horizontal line indicates the assumed level of the surface of the immobile bed,  
1198the dashed brown horizontal line the top of the assumed layer of rolling and sliding bedload,  
1199and the dotted black horizontal line the top of the layer of saltating bedload. ADVP  
1200measurements in bin numbers smaller than 37 are outside the sensitivity range of the ADVP  
1201transducers for the present ADVP configuration.

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1204**Figure 3:** Time-averaged ADVP profiles of the longitudinal velocity estimated with the  
1205 pulse-pair algorithm (Equation 4). The dashed line represents a linear fitting of the measured  
1206 velocity against  $\log(30z/k_s)$ . The distance (m) above the immobile bed is indicated by  $z$ , and  
1207 the equivalent grain roughness  $k_s$  is taken as 0.01 m. In order to avoid singularities, the bin  
1208 containing the surface of the immobile bed has been plotted at  $z = 0.001$  m. (a) Experiments  
1209 in the second series of test with nominal flow depth of 0.14 m (Table 1); (b) Experiment  
1210 Q795L in the main series of experiment. The symbol (v) denotes experiments without  
1211 bedload sediment transport, and the symbol (x) denotes experiments with bedload sediment  
1212 transport.

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1214**Figure 4:** Near-bed bins including the bin in which the surface of the immobile bed is  
1215 situated. The upper part of that bin is situated in the flow where bedload sediment particles  
1216 roll and slide on the bed. Therefore the bin containing the surface of the immobile bed is  
1217 identified as the bin with minimum non-zero velocity measured by the ADVP. Figure on scale

1218

1219**Figure 5:** Temporal evolution of the magnitude of the raw backscattered signal,  $I^2$  [ $V^2$ ],  
1220 during the 614 s Q1000L experiment. The colorbar defines the scale of  $I^2$ . The vertical axis  
1221 shows the part of the water column between bin numbers 50 and 65 where the magnitude  
1222 reaches maximum values. The 614 s duration is divided in five periods of quasi-constant  
1223 conditions. Digital videography was performed during sequences of 10 s with an interval of  
1224 60 s, as indicated by the labels V1 to V11.

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1226**Figure 6:** In-phase component  $I$  [V] of the complex range gated backscattered raw return  
1227 signal measured at PRF = 1000 Hz by one of the receivers in the Q795L experiment from  $t =$   
1228 2 s to 2.2 s after the beginning of the experiment.

1229

1230**Figure 7:** Power spectral density of the four beam velocities in bins [3, 2, 1] above the bin  
1231that contains the surface of the immobile bed in the Q795L experiment. Velocity [ $\text{m s}^{-1}$ ] on  
1232the abscissa is calculated from observed beam Doppler frequencies, and transformed to the  
1233horizontal component.

1234

1235**Figure 8:** Time series of velocities sampled at a frequency of  $\text{PRF/NPP} = 31.25$  Hz in the  
1236Q795L experiment in bins 54 and 55 (clear water), 56 (saltating bedload layer), 57 (rolling  
1237and sliding bedload layer), and 58 (containing the surface of the immobile-bed).

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1239**Figure 9:** Results of time-averaged velocities measured with ADV (profiles) and particle  
1240tracking videography (gray distribution functions) for experiments Q630 (top row), Q795  
1241(middle row) and Q1000 (bottom row). Test with low (left column) and high (right column)  
1242acoustic power. Experiments have been divided into periods of quasi-homogeneous  
1243conditions (Table 1 and Table S1 in the supporting information; period 1: blue, period 2:  
1244green, period 3: black; period 4: cyan, period 5: mauve). Note that the horizontal axis only  
1245refers to the time-averaged velocities measured with ADV, but has no relation to the  
1246distribution function based on the videography.

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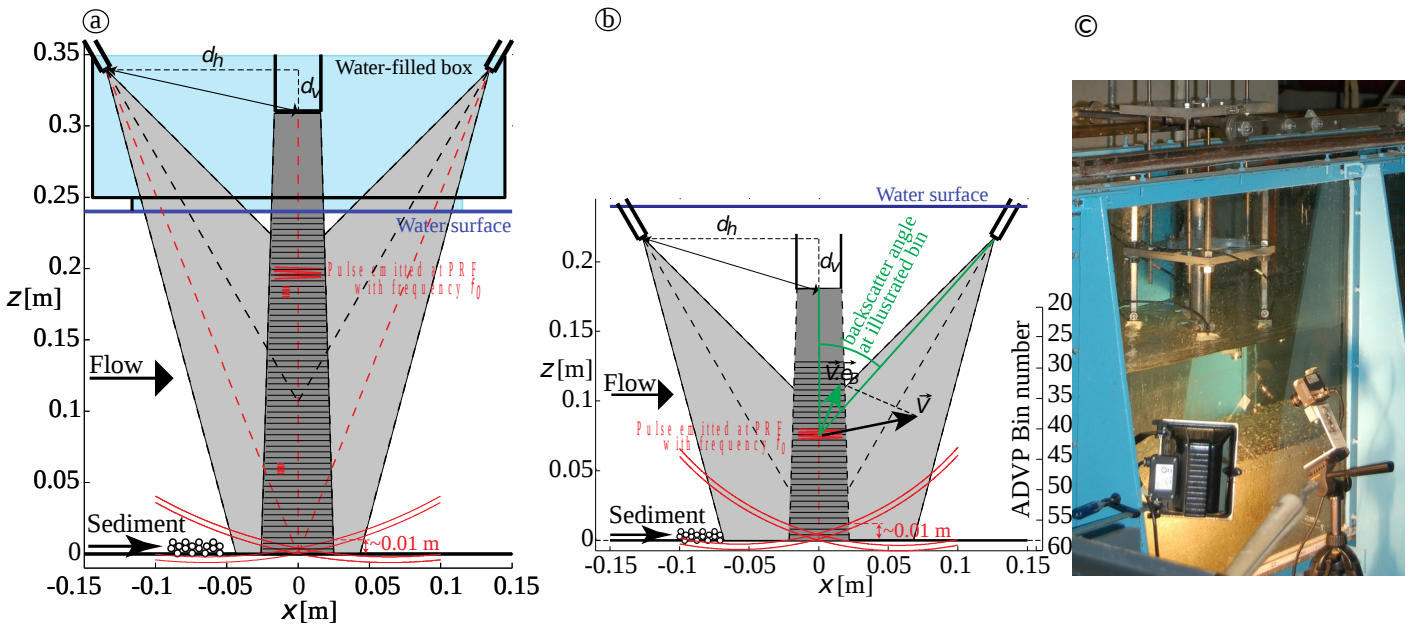
1248**Figure 10:** Time series of quasi-instantaneous velocities, including turbulent fluctuations,  
1249measured with ADV in the bin containing the immobile bed and the bin just above (Figure 9  
1250and Table 1) and estimated from the videography with the Optical Flow algorithm (thick red  
1251line) for experiments Q630L (top row), Q795L (middle row) and Q1000L (bottom row). The  
1252horizontal axis indicates time from the beginning of the experiment. Two 10 s sequences of  
1253videography are shown (Figure 5). Additional videos showing the bedload transport are  
1254provided online as supporting information.

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1256**Figure 11:** a) Sediment velocity in the bed load layer as a function of the shear velocity  $u_*$ .  
1257measured with ADV (black) and estimated from videos by PTV (grey). The two lines  
1258represent predictions according to Equation 7 for  $a = 4.4$  and  $a = 13.2$ , respectively. b)  
1259Thickness of the layer of rolling and sliding bedload (indicated in Figure 9) estimated from

1260ADVP as a function of the shear velocity  $u_*$ . The two lines represent prediction according to  
1261Equation 8 for  $d = d_{50} = 0.0008$  m and  $d = 0.0015$  m. For both a) and b), circles represent the  
1262experiments with simultaneous videography (main series), squares the second series  
1263experiments with flow depth 0.14 m, and crosses the second series experiments with flow  
1264depth 0.24 m. Because results for different periods within the same experiment were not  
1265significantly different, only one data point per experiment is shown, obtained as the average  
1266of results of all periods.

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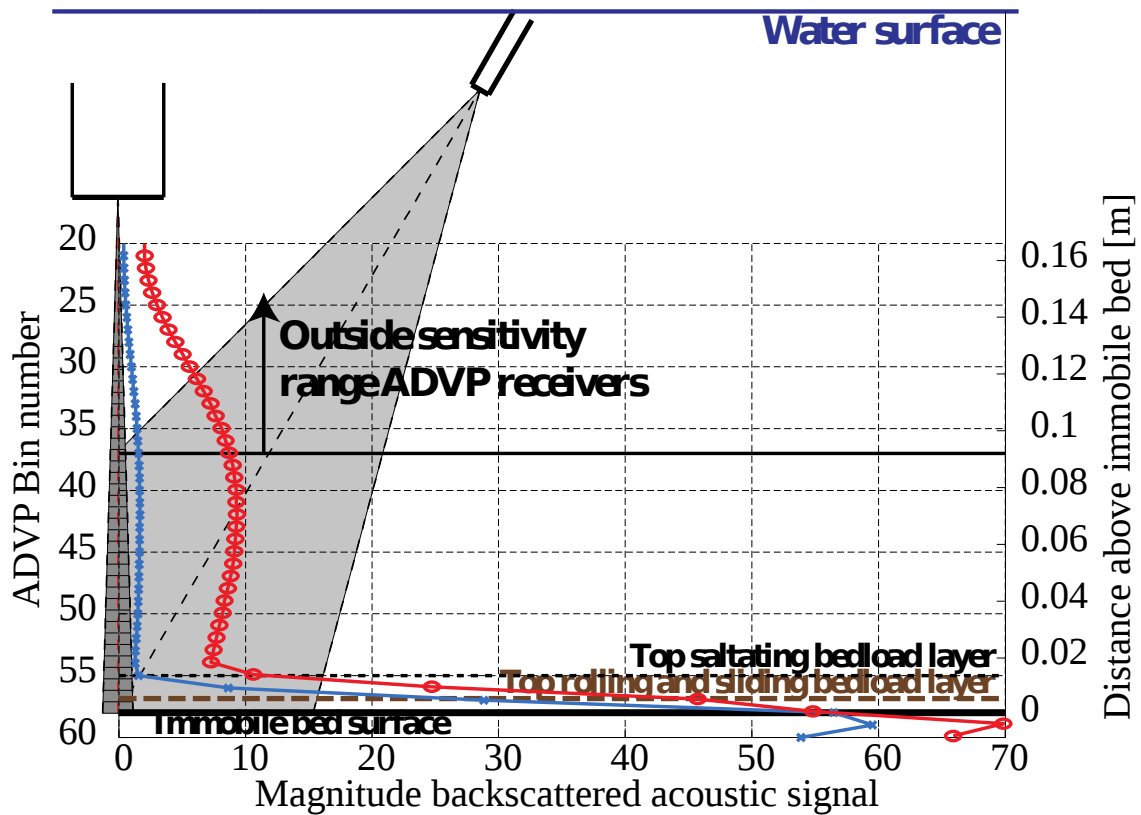
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9(a) Standard ADVP configuration optimized for flow measurements in the body of the water column. The  
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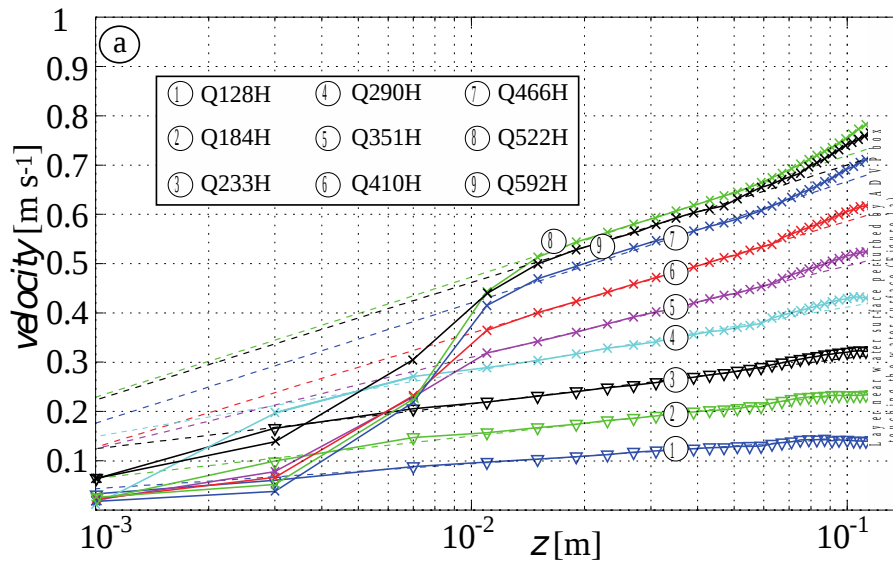
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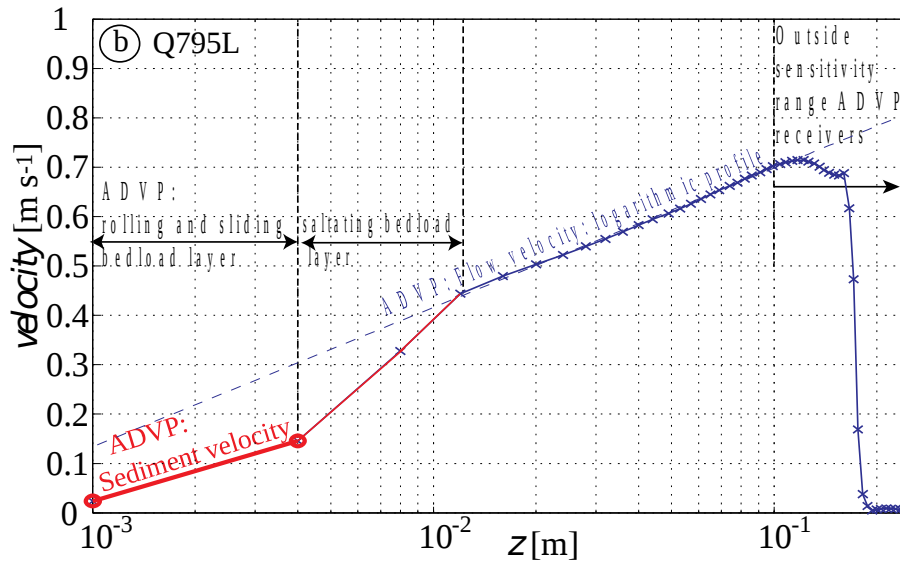
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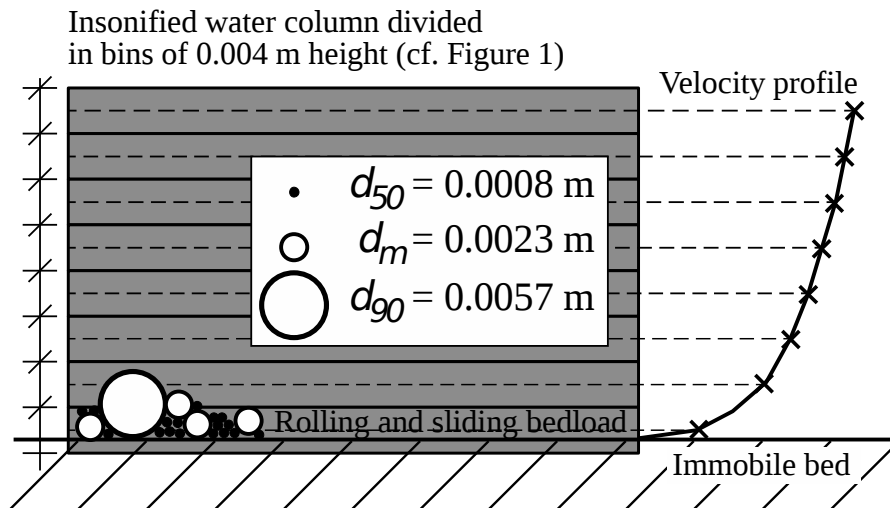


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42 **Figure 3:** Time-averaged ADVP profiles of the longitudinal velocity estimated with the pulse-pair algorithm  
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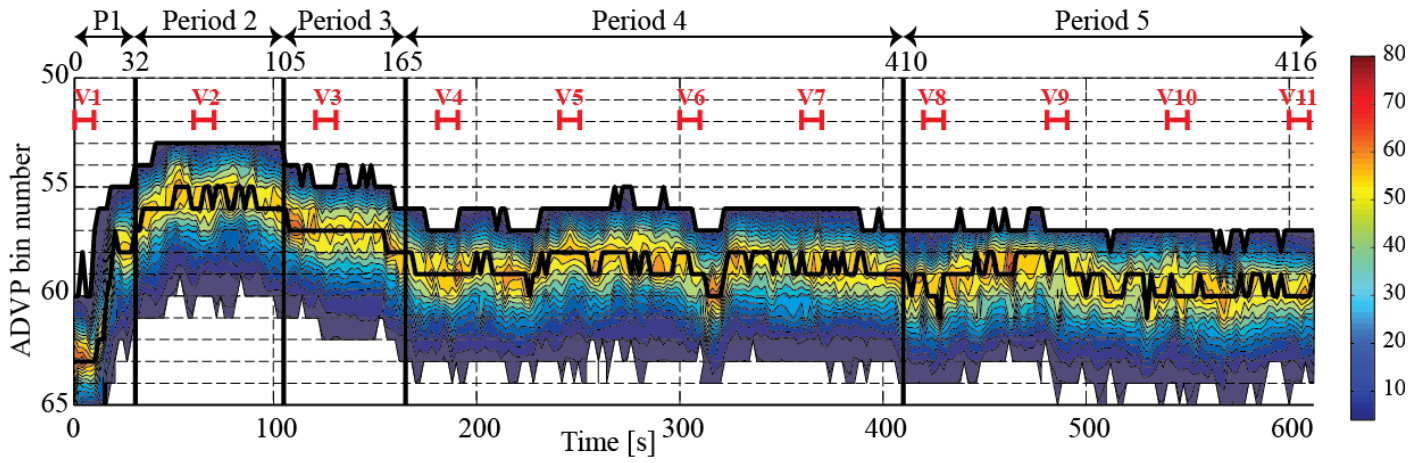
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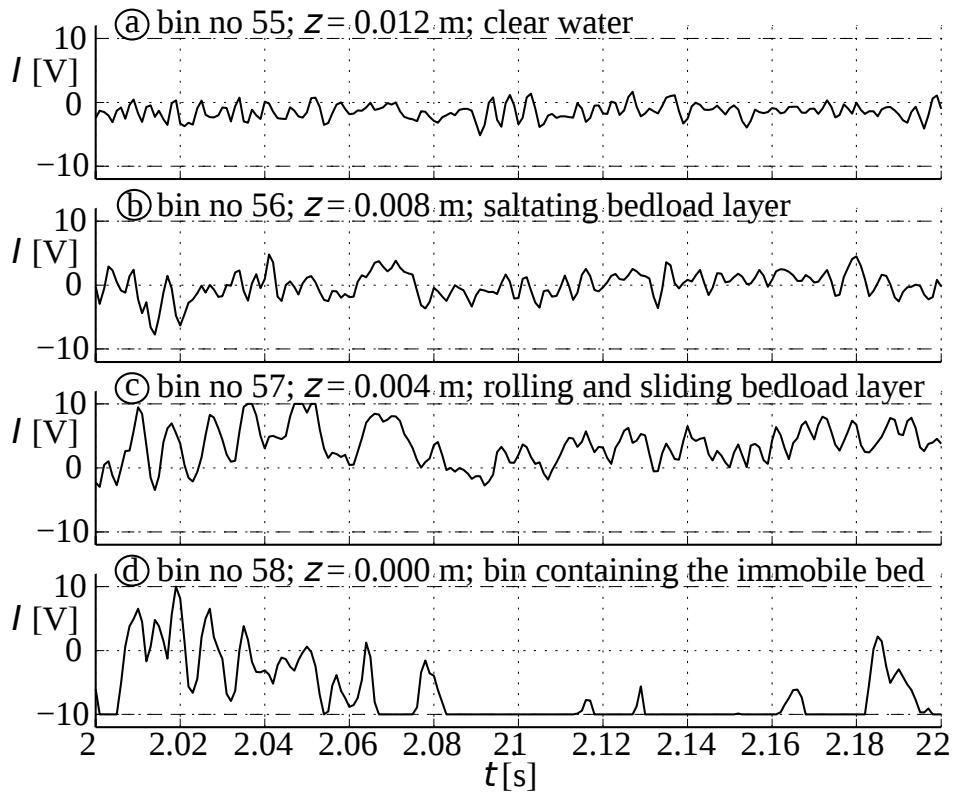
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68**Figure 5:** Temporal evolution of the magnitude of the raw backscattered signal,  $I^2$  [ $V^2$ ], during the 614 s  
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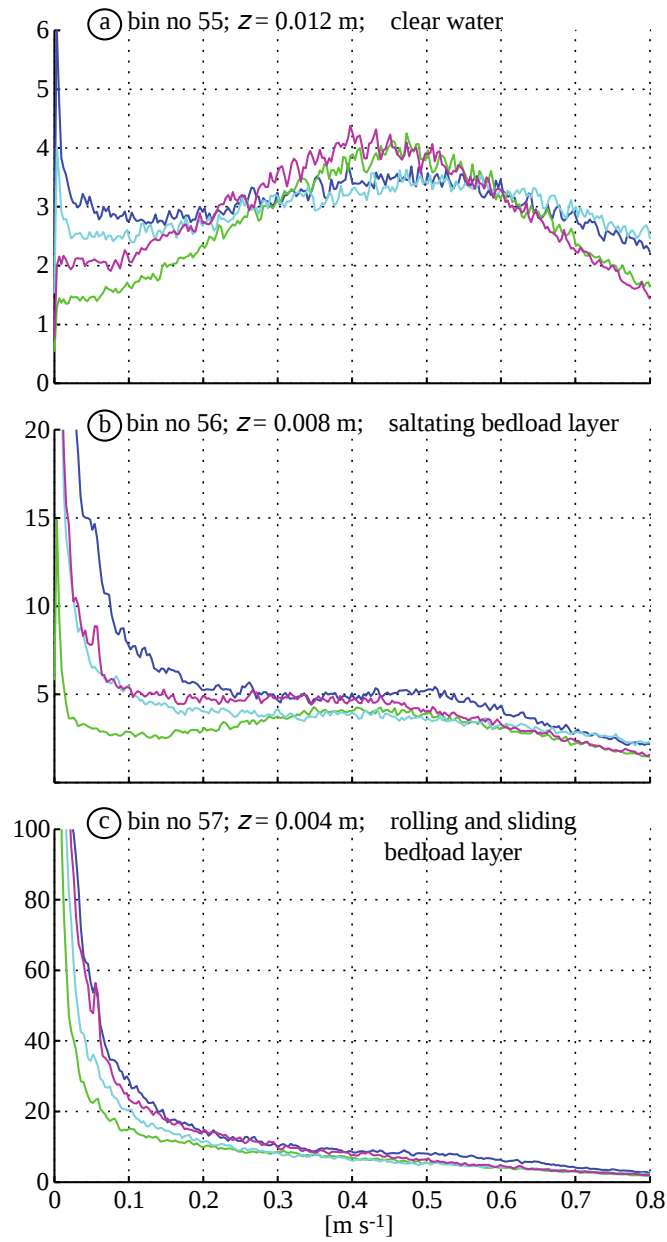
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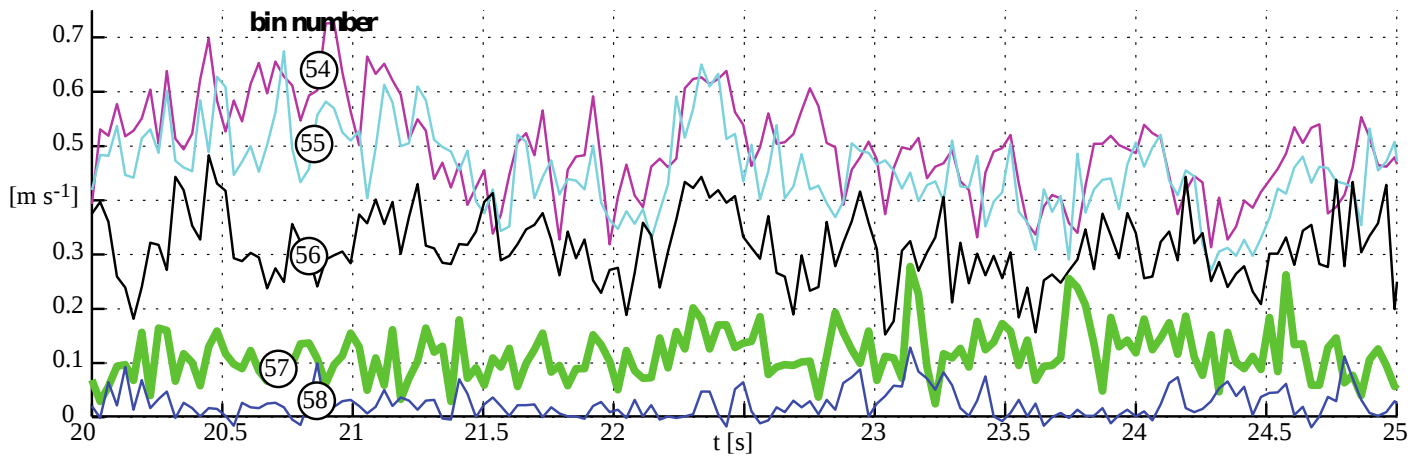
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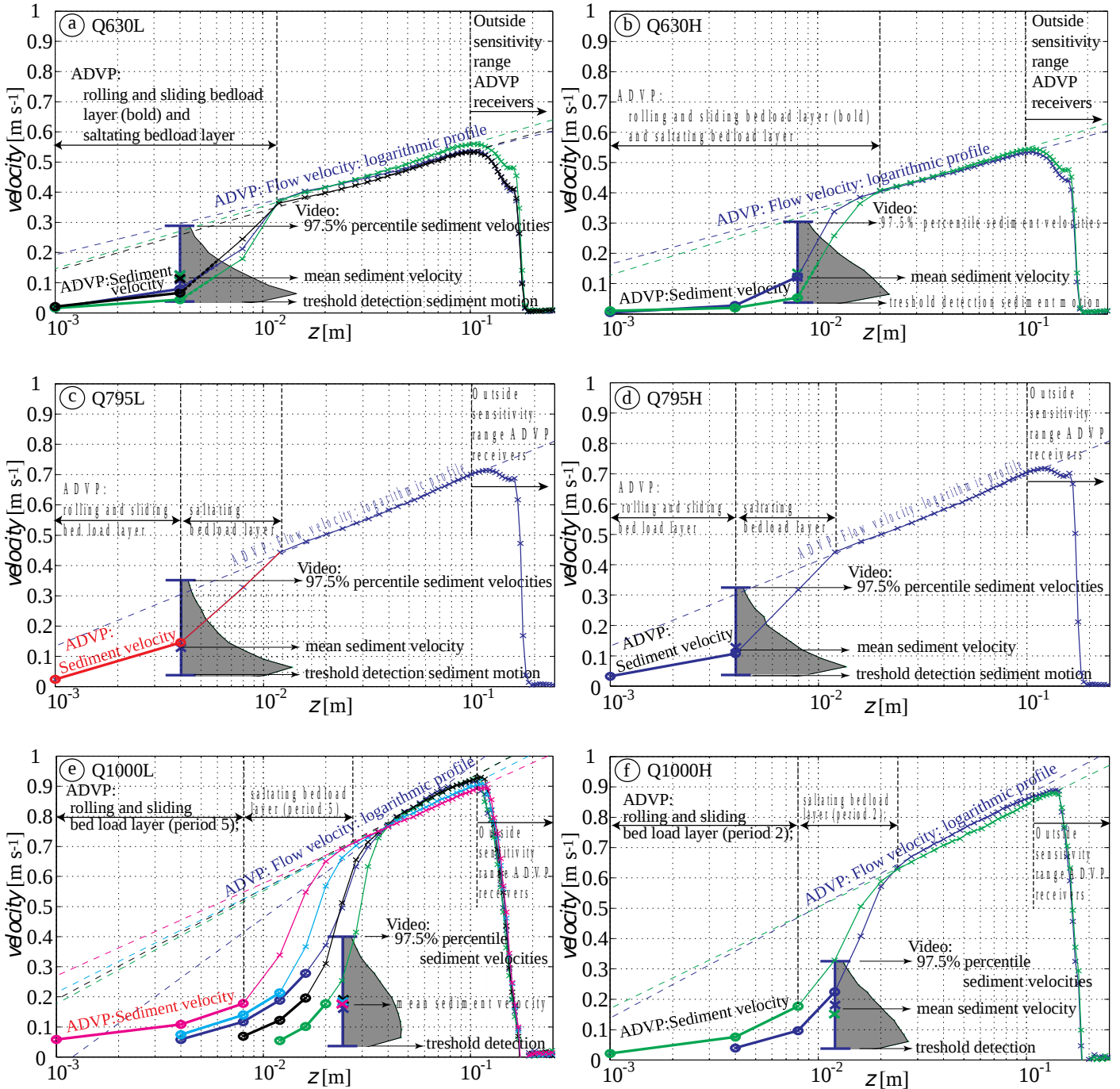
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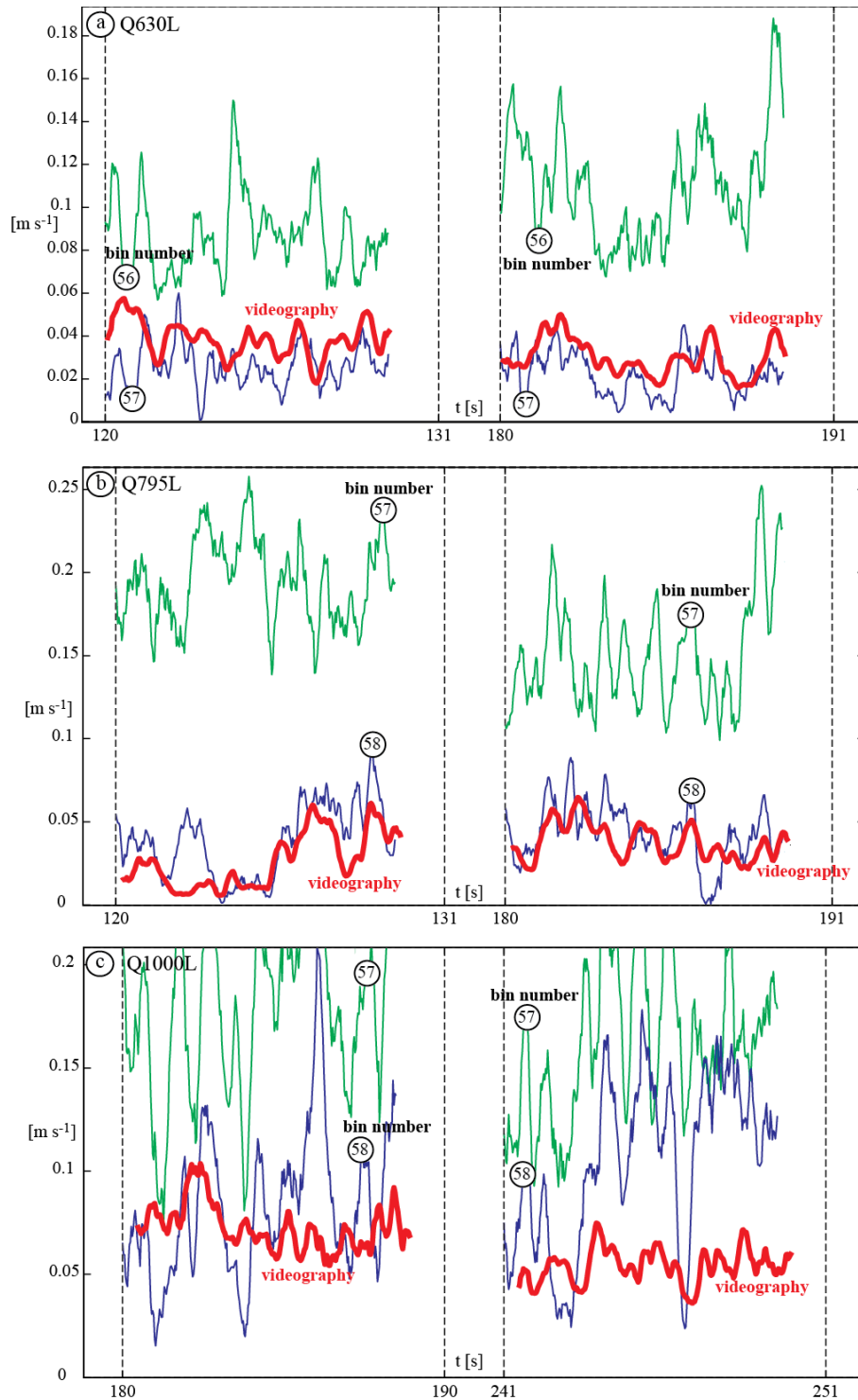
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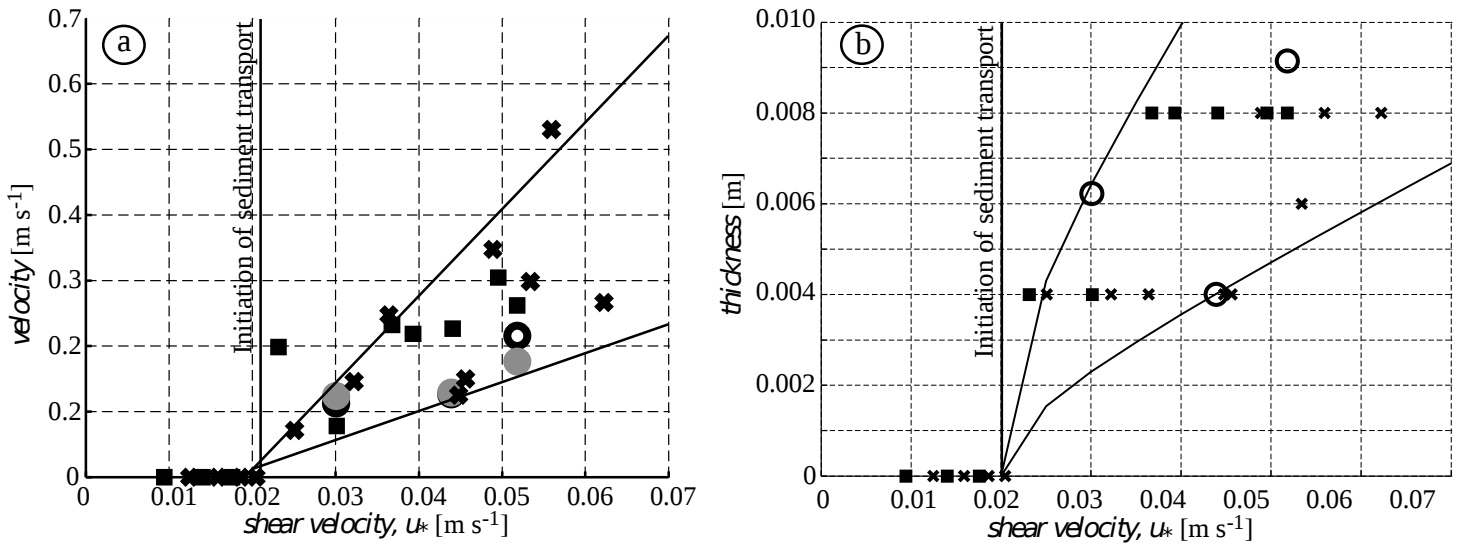
101 **Figure 9:** Results of time-averaged velocities measured with ADVP (profiles) and particle tracking videography  
 102 (gray distribution functions) for experiments Q630 (top row), Q795 (middle row) and Q1000 (bottom row). Test  
 103 with low (left column) and high (right column) acoustic power. Experiments have been divided into periods of  
 104 quasi-homogeneous conditions (Table 1 and Table S1 in the supporting information; period 1: blue, period 2:  
 105 green, period 3: black; period 4: cyan, period 5: mauve). Note that the horizontal axis only refers to the time-  
 106 averaged velocities measured with ADVP, but has no relation to the distribution function based on the  
 107 videography.



108

109 **Figure 10:** Time series of quasi-instantaneous velocities, including turbulent fluctuations, measured with ADV  
 110 in the bin containing the immobile bed and the bin just above (Figure 9 and Table 1) and estimated from the  
 111 videography with the Optical Flow algorithm (thick red line) for experiments Q630L (top row), Q795L (middle  
 112 row) and Q1000L (bottom row). The horizontal axis indicates time from the beginning of the experiment. Two  
 113 10 s sequences of videography are shown (Figure 5). Additional videos showing the bedload transport are  
 114 provided online as supporting information.





117 **Figure 11:** a) Sediment velocity in the bed load layer as a function of the shear velocity  $u_*$ , measured with  
 118 ADVP (black) and estimated from videos by PTV (grey). The two lines represent predictions according to  
 119 Equation 7 for  $a = 4.4$  and  $a = 13.2$ , respectively. b) Thickness of the layer of rolling and sliding bedload  
 120 (indicated in Figure 9) estimated from ADVP as a function of the shear velocity  $u_*$ . The two lines represent  
 121 prediction according to Equation 8 for  $d = d_{50} = 0.0008$  m and  $d = 0.0015$  m. For both a) and b), circles  
 122 represent the experiments with simultaneous videography (main series), squares the second series experiments  
 123 with flow depth 0.14 m, and crosses the second series experiments with flow depth 0.24 m. Because results for  
 124 different periods within the same experiment were not significantly different, only one data point per  
 125 experiment is shown, obtained as the average of results of all periods.