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The anatomy of effective discharge: the dynamics of coarse sediment transport revealed using continuous bedload monitoring in a gravel-bed river during a very wet year

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Abstract

Indirect, passive approaches for monitoring coarse bedload transport could allow cheaper, safer, higher-resolution, longer-term data that revolutionises bedload understanding and informs river management. Here, insights provided by seismic impact plates in a downstream reach of a flashy gravel-bed river (River Avon, Devon, UK) are explored in the context of plate performance. Monitoring of a centrally-situated plate (IP1) during an extremely wet 12-month period demonstrated that impacts were related to discharge as a measure of transport potential ($R^2 = 0.38$) but that factors other than transport limitations are important. Analysis of discrete flow events revealed consistent rising-limb and falling-limb impact spikes biased toward the latter for larger events. Such patterns may result from disruption of the upstream armour layer (rising limb) and supply enhancements related to both upstream mass bank failures and/or flood routing of non-local sediment sources (falling limb). Installation of additional impact plates indicated that plate IP1 was indeed dominantly related to instantaneous discharge, that a three-plate lateral array somewhat better

explained impact variability ($R^2 = 0.49$), and that the bedload track shifts laterally with discharge. Aggregating event-total IP1 impacts against volumetric discharge further increases explanation as intra-event and stochastic bedload factors are subsumed but left 26% unexplained variance related to the unsampled bedload mass, inter-event supply differences, and attributes of plate performance. Annualising the data created an impact-based 'effective discharge' for this extremely wet year that was closer to morphological bar-full in magnitude than bankfull, but the preceding results imply this outcome is related as much to supply limitations as transport limitations. Overall, passive approaches offer a liberating prospect for bedload monitoring, capable of producing insights only achievable through high resolution, extended time periods. Such results could potentially inform threshold conditions and geomorphological effectiveness of flows for future river management strategies.

Key words: coarse bedload transport, seismic impact plates, effective discharge, fluvial geomorphology, river management

Introduction

The dynamics of river bedload transport is a critical element in defining river channel morphology and the ecosystem service potential of river systems (Gilvear *et al.*, 2013). The balance between rates of sediment supply and transport underpins the existing quality, underlying potential and threats to aquatic habitats, while erosion and deposition processes associated with changes in channel morphology frequently present significant risks to floodplain development and critical infrastructure. Accurate characterisation of bedload dynamics is thus central to a better geomorphological understanding of river systems under threats related to changing climate, changing priorities in water resources and land management (Palmer 2009;

Palmer *et al.*, 2008, 2009), and to river (and flood risk) management and restoration schemes addressing regional sediment management concerns (e.g., Downs and Gregory, 2004; Thorne *et al.*, 2010).

Measurement of river bedload dynamics has traditionally required direct monitoring using hand-held or winched portable bedload samplers during storm events, various types of trap designed to intercept the transported load over a given period, the deployment of tracer particles, or periodic morphological re-survey (Rickenmann *et al.*, 2012). Such approaches are labour-intensive, can involve significant safety concerns, and often have limited applicability to geomorphologically-relevant time periods. Thus, in most practical applications, the dynamics of bedload transport has been determined using empirical formulae and numerical simulation (e.g., Pitlick *et al.*, 2009; Wilcock *et al.*, 2009). However, the simplifications inherent to these equations relative to the complexities of bedload transport processes mean that uncertainties in rate estimates are rarely below 50 per cent (Wilcock, 2001) and may extend to several orders of magnitude (Gomez and Church, 1989; Bathurst, 2007).

Unsurprisingly, such approaches have frequently focused on the transport-limiting factors inherent to bedload dynamics, and have facilitated the endurance of magnitude-frequency based interpretations of fluvial systems, such as that inherent to the important concept of effective discharge (Wolman and Miller, 1960).

Methods for characterising bedload transport have now broadened to include a suite of *indirect* methods that include active approaches based on recording of bedload displacement by radar, sonar or acoustic Doppler instruments and the use of 'smart' tracers (Gray *et al.*, 2010a), and passive approaches based on recording the passage of bedload particles past a hydroacoustic or impact sensor. Passive techniques offer an opportunity to record high resolution spatial and temporal

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3 73 measurement of bedload transport over extended time periods (Gray *et al.*, 2010a),
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5 74 using relatively low cost, portable and non-intrusive devices. Such surrogate
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7 75 monitoring is argued to offer a 'revolutionary concept in fluvial sedimentology'
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10 76 allowing safer, more frequent, more accurate and less expensive bedload data
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12 77 collection to help manage the world's sedimentary resources (Gray *et al.*, 2010b).
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15 78 Passive bedload-surrogate monitoring systems have been variously classified but
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17 79 consist generally of 'geophones' that record the vibration caused by bedload
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19 80 particles colliding with a rigid-bodied sensor (a pipe, plate or column), 'hydrophones'
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21 81 that record the ambient noise of inter-particle collisions near the sensor, or a hybrid
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23 82 (Downing, 2010; Froehlich, 2010; Mizuyama *et al.*, 2010a). The former are secured
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25 83 flush with the channel bed and record impacts via the vibration of an accelerometer
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27 84 or geophone whereas the latter are mounted low in the water column to record the
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29 85 acoustic waves of sediment (and turbulent water) passing the instrument. There is a
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31 86 rapidly growing body of literature associated with passive bedload monitoring
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33 87 (summaries in Gray *et al.*, 2010a, b; Rickenmann *et al.*, 2014), with a large
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35 88 proportion of the research focused upon the potential for their use in establishing
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37 89 bedload transport *rates* (e.g., Mizuyama *et al.*, 2010a; Rickenmann and McArdeil,
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39 90 2008; Turowski and Rickenmann, 2011; Rickenmann *et al.*, 2012).
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44 91 Rigid-bodied sensors log sediment transport when the momentum of the clast
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46 92 striking the plate is sufficient to be recorded either acoustically or seismically as an
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48 93 electrical wave. Impacts can be recorded as a simple pulse when the impact
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50 94 exceeds a certain electrical threshold, as a wave of variable amplitude that is
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52 95 potentially correlated with particle size (e.g., Beylich and Laute, 2014; Rickenmann
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54 96 *et al.*, 2014; Tsakiris *et al.*, 2014; Wyss *et al.*, 2014; Barrière *et al.*, 2015a), or as a
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56 97 multi-frequency acoustic response with the potential to monitor the transport of
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98 mixed-size clast impacts (Mizuyama *et al.*, 2010a; 2010b). The particle size
99 recorded thus varies with the type of device with the minimum size of the recorded
100 sediment reported to range from 4 to 30 mm depending on the sensor and
101 measurement set-up (Gray *et al.*, 2010b; Rickenmann *et al.*, 2012), confirming that
102 impact plates generally record *coarse* bedload transport rather than the movement of
103 finer gravels or coarse sands.

104 Similar to debates about the representativeness and instrument-dependency of
105 bedload sediments captured through direct monitoring (Bunte and Abt, 2005, 2009;
106 Bunte *et al.*, 2008, 2010), there is some uncertainty as to how to interpret the signal
107 of passive recording instruments. Sensors are subject to grain-size dependent and
108 transport-style effects. Using a piezoelectric crystal impact plate sensor,
109 Rickenmann and Fritschi (2010) and Rickenmann and McArdell (2007) noted the
110 increasing strength of geophone signal response as particles increase in size from
111 20 to 30 mm (subsequently corroborated by Rickenmann *et al.*, 2012, 2014).

112 Particle shape may also cause variation in recorded impacts because particles of
113 similar weight and dimensions may be transported by different mechanisms
114 (Turowski and Rickenmann, 2009). Rounded particles are more likely to roll and
115 thus record a greater number of impacts than a similarly-sized particle transported by
116 saltation or sliding (Turowski and Rickenmann, 2009) whereas pulses of mixed-load
117 sediment may be under-represented depending on the sensitivity of the sensor
118 (Beylich and Laute, 2014). In practical terms, over-counting of sediment resulting
119 from multiple impacts registered by rolling particles is minimised by having a small
120 plate size which restricts repeated contact (Reid *et al.*, 2007) and setting the
121 detection frequency to suppress very closely timed impulses. However, a small plate
122 introduces the prospect of under-representing particles transported with longer

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3 123 saltation lengths during very high flows (e.g., Chatanantavet *et al.*, 2013) while the
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5 124 detection frequency must still be high enough to minimize the significant
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7 125 underestimation of particle counts during very high intensity transport events.
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9 126 Neither plate size or detection frequency addresses potential sediment size-
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11 127 dependency in impacts counts but we may assume that the variability in impact
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13 128 response related to grain size, shape and transport mode is somewhat cancels out
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15 129 when large number of particles are involved.
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19 130 Despite these uncertainties in interpreting impact counts, there is increasing
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21 131 evidence for a robust correlation between summed impact counts and total bedload
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23 132 mass over event-scale and longer time periods (Rickenmann and McArdell, 2007,
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25 133 2008; Beylich and Laute, 2014; Rickenmann *et al.*, 2014). Furthermore, while
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27 134 attempts to precisely calibrate individual sensors to produce rating curves that
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29 135 *directly* estimate bedload transport rates will remain subject to a lengthy refinement
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31 136 period (Rickenmann *et al.*, 2014), this reflects only one way in which impact sensors
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33 137 might meet their 'revolutionary' potential in bedload understanding. A
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35 138 complementary activity, investigated herein, is to use the sensor's capacity for high
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37 139 resolution continuous monitoring to examine the dynamics of bedload initiation,
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39 140 cessation and relative intensity of transport (see also Turowski, *et al.* 2011) in
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41 141 comparison to discharge over minute-to-annual timescales.
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46 142 Whereas impacts plates have been used to study network-scale sediment dynamics
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48 143 (e.g., Reid *et al.*, 2007; Lane *et al.*, 2008; Raven *et al.*, 2009, 2010), reach-scaled
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50 144 applications have only recently begun to emerge (Mao *et al.*, 2014; Barrière *et al.*,
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52 145 2015b). The focus here concerned insights achieved from high-resolution recording
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54 146 of coarse bedload impacts in a meandering reach of a gravel-bedded river for a
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56 147 twelve-month period that turned out to be the wettest on record. Interpretation of the
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148 recorded impacts highlighted competing transport- and supply-related controls on
149 enhanced bedload dynamics related to the extremely wet period, but also reflected
150 the performance characteristics of the instrument itself. Aggregating the results from
151 5-minute intervals through to an annual summary of impacts revealed details about
152 the anatomy of effective discharge (*i.e.*, the shape and characteristics of the
153 distribution of sediment transporting flows), including its dependency on transport-
154 limiting factors. Better understanding the (limits to) insights gained in this manner will
155 help determine the extent to which bedload transport underpins the ecosystem
156 service potential of river systems, the dynamics of fluvial activity under scenarios of
157 more frequent extreme events and, ultimately, whether arrays of such sensors
158 should be part of routine monitoring of river systems.

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160 **Study area – bedload context**

161 The River Avon, south Devon, UK, covers a catchment area of 110.5 km² and flows
162 approximately 40 km from its headwaters on Dartmoor National Park to the mouth at
163 Bigbury-on-Sea (Figure 1a). The catchment is predominantly rural and dominated by
164 rough hillslope grazing in the upper reaches and mixed arable and pasture in the
165 middle and lower reaches. It provides regionally important habitat for salmonid
166 species, notably Atlantic salmon (*Salmo salar*). In the Dartmoor uplands (*c.* 400 m
167 amsl), igneous granite overlain by peat soils produces cascading boulder-bedrock
168 channels with low rates of sediment supply except in locations where historical
169 placer mining released finer-grained alluvial materials from floodplains (Bradley,
170 1990). In contrast, the slates, shales and grits that characterise the mid- and lower-
171 reaches of the catchment result in a high supply of gravel and cobble sediments

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3 172 focused in river bank locations (Twohig, 2014). The mid-reaches are set into steep-
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5 173 sided valleys with outcrops that create bedrock-controlled alluvial channel
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7 174 morphology. Morphology associated with a fully alluvial, actively meandering, gravel
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9 175 bed channel develops only in the lowest several kilometres of channel. Here, a
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11 176 sharp break from gravel-cobble basal bank sediments to loam-silt upper layers
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13 177 above may be indicative of floodplain formation accelerated by the deposition of fine
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15 178 sediment wastes that resulted following an intensive period of tin mining during the
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17 179 15th and 16th centuries AD or possibly earlier (Thorndycraft *et al.*, 1999, 2003, 2004).
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19 180 The study site is located on a 400 m section of the lower main channel (Figure 1b)
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21 181 and has a bankfull water surface slope of 0.0023.
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26 182 Figure 1 near here
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29 183 The lower Avon is subject to a flashy flow regime resulting from frequent heavy
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31 184 rainfall events on the Dartmoor uplands and the trellis drainage pattern of steep
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33 185 tributaries joining throughout the mainstem length (Figure 1a). Average annual
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35 186 rainfall ranges from 2,200 mm in the Dartmoor headwaters to around 1,000 mm at
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37 187 the coast. The hydrological influence of agricultural flow abstractions and drainage
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39 188 and the Avon Dam, which impounds 12.6 km² of the Avon headwaters (Bogle *et al.*,
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41 189 1959), are presumed to be minimal at the study site during high flows. The study
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43 190 reach is characterized by sub-angular surface gravel sediments partially derived
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45 191 from rapid erosion of coarse basal bank sediments. A median surface grain size of
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47 192 33 mm from Wolman counts versus 15 mm from sieved bulk samples is suggestive
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49 193 of mild bed armouring (Hassan *et al.*, 2006 criterion), but frequent gravel mobility is
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51 194 suggested by convergence of surface and bulk grain size at $\approx D_{60}$ (Figure 2).
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56 195 Figure 2 near here
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197 **Methods**

198 Bedload transport was monitored using ‘Benson-type’ seismic impact plate sensors
199 modified slightly from those described by Carling *et al.* (2002), Richardson *et al.*
200 (2003) and Reid *et al.* (2007) by the addition of more memory and a more rigid
201 enclosure with a very lightly curved top surface intended to improve stability. The
202 sensors consist of a stainless steel plate (150 x 130 x 6 mm) fitted with an
203 accelerometer to convert mechanical energy to electrical energy (based on a RS
204 piezoceramic bi-morph transducer), coupled with a Tinytag 1200 data logger to
205 permit continuous time series recording of bedload transport (Figure 3). The
206 accelerometer records impacts on the metal plate when the impact generates signal
207 amplitudes of more than ≈ 20 mV, implying a minimum recorded particle mass of
208 about 0.5 g (I. Benson, *pers. comm*), ranging up to around 100 V (> 2 kg particle). It
209 is set to record at 5Hz (*i.e.*, suppressing counts less than 0.2 s apart) which limits
210 multi-counting of rolling particles but also restricts the maximum sediment count to 5
211 counts per second. Because the plates record a pulse rather than a wave of energy,
212 and thus do not distinguish between particles of different size (mass) striking the
213 plate, they cannot be used to *directly* establish sediment load (recent progress in
214 estimating the grain size distribution of bedload transport: Taskiris *et al.*, 2014; Wyss
215 *et al.*, 2014; Barrière *et al.*, 2015a; an indirect method: Soar and Downs, *in*
216 *preparation*). As each plate represents only a small area of the channel bed they
217 provide limited coverage of transport across the channel width, but this also serves
218 to limit multi-counting of rolling particles. The plates were bolted onto a concrete
219 paving slab (400 x 400 x 60mm) to provide stability. An 80 mm diameter hole drilled

220 through the slab accommodates the logger housing. The slab was placed in the river
221 bed flush with the bed material.

222 **Figure 3 near here**

223 The primary plate (IP1) was installed in late April 2012 in a locally-steep, straight
224 reach, with a centrally-positioned maximum velocity filament interpreted to carry the
225 bulk of the bedload transport. In December 2012, three additional plates were
226 installed to record attributes across and along the channel profile: two were set
227 laterally (IP2 and IP3, respectively) at the first and third quartiles of the cross-section
228 containing IP1 while an additional plate was placed centrally 10m upstream (Figure
229 4) . Data were logged at 2.5 minute intervals, a period judged to strike a balance
230 between minimising saturation of the logger in terms of its maximum recordable
231 counts (255) during one logging interval but maximising the time period between
232 data downloads (ca. 3.5 months, in this case).

233 **Figure 4 near here**

234 Bedload count data were correlated directly against discharge measurements for the
235 period 28/4/12–1/5/13 at the Environment Agency's 'Loddiswell' gauging station (1.2
236 km upstream of the study site), by summing two 2.5-minute bedload counts and
237 interpolating between 15-minute 'instantaneous' discharge records to result in 5-
238 minute data pairs. As only one minor tributary enters the Avon between the
239 Loddiswell gauge and the study site no areal scaling was applied to the discharge
240 records, and stage data from the study site (recorded using a Campbell CS450
241 Submersible Pressure Transducer) indicated a robust correlation between
242 Loddiswell discharge records and flow elevations at the study site. Water surface

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slope was monitoring during a subsequent winter season using two In-Situ Inc. Aqua
TROLL 200 data loggers.

Results

The monitoring period coincided with the wettest 12-month period of record and
included 20 overbank events, the instantaneous flood of record (peaking at 124.2
 m^3s^{-1} : 7/7/12) and the greatest mean daily flow of record ($57.0 \text{ m}^3\text{s}^{-1}$: 22/12/12). The
peak flow, derived from a series of convective rainfall events that caused extensive
sudden-onset flooding across south-west England, had a return period of ≈ 87 years
(Gumbel Extreme Value method, to the end of WY2013) and was approximately 30%
greater in magnitude than the previously recorded instantaneous peak ($95.5 \text{ m}^3\text{s}^{-1}$).
Whereas the 2012-13 daily mean flows had only a minor impact on the 36-year
record of flow duration statistics, the study period in isolation represented a
significant (wet) departure from the long term average (Figure 5).
Bedload activity during the monitoring period is thus probably highly atypical but,
experimentally, represents an extraordinarily rich data set from which to investigate
insights and constraints on bedload transport obtained using impact plates. The
results reflect both transport- and supply-limited bedload dynamics in combination
with limits imposed by the experimental design and instrument constraints. Overall,
bedload activity and intensity is expected to vary as a function of (1) near-
instantaneous tractive forces applied to the channel bed, (2) granular interactions
(hiding, packing, friction angle, etc.) that govern the dynamical behaviour of bedload
sheet migration and surface armour disruption, (3) reach-scale variability in sediment
supply, (4) catchment-scale variability in sediment supply, (5) attributes related to

experiment design and the relative placement of the impact plate(s) and (6) attributes of the measurement device. These facets are investigated below.

Figure 5 near here

Instantaneous fluctuations: tractive forces and threshold of detection

Raw impact count data (Figure 6) indicates a strong *general* correspondence between high flow events and high impact counts at plate IP1. Counts are aggregated into 92,284 five-minute intervals allowing a maximum of 510 impacts in each interval. Saturated counts were observed only after the flow of record, with 82% of these instances (114/139) occurring during one flood event on 6-8th October 2012 (peak discharge $79.8 \text{ m}^3\text{s}^{-1}$). Over individual 5-minute periods, Figure 7 illustrates a considerable variability of impacts with discharge ($R^2 = 0.38$, as a power relationship). Progressively constraining the flow data to those points $<65 \text{ m}^3\text{s}^{-1}$ (to exclude the record high flows) and then $<32 \text{ m}^3\text{s}^{-1}$ (to exclude all overbank flows) does not significantly alter the explained variance ($R^2 = 0.36, 0.37$, respectively). Indeed, explained variance improves only once all flows above 'bar full' values are excluded ($\approx 20 \text{ m}^3\text{s}^{-1}$), and then only mildly ($R^2 = 0.45, I=0.032Q^{2.57}$ where I =impacts and Q =discharge). Clearly, there is a high degree of variability inherent to the data set.

Generally, Figure 7 illustrates the gradual onset of bedload transport over the threshold entrainment value followed by rapidly increasing rates of transport for flows up to $\sim 15 \text{ m}^3\text{s}^{-1}$, a reduction in transport rates until overtopping and slowly increasing rates thereafter. This may suggest an initial suite of transport-limited impact counts, resulting from easily-entrained locally-available materials (Habersack *et al.*, 2001), followed by supply-related limitations in higher flows, or some backwater influence of the downstream riffle crest (until sufficiently overtopped). Alternatively (see

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Introduction), variability may relate to artefacts of the experimental design and performance of the instrument itself, for instance related to sediment size, mode of transport, changing bedload transport pathways, or increasing saltation hop lengths during higher velocity flows.

Figure 6 and 7 near here

To investigate transport-related limitations directly as a function of tractive forces, estimates of local shear stress were developed based on flow depth immediately above the centrally-positioned impact plate IP1. Flow depths were obtained from water elevation data and cross-section surveys, and energy gradients were based on channel bed surveys and continuous monitoring of water surface slopes over one meander wavelength during a subsequent winter season (peak flow $41.9 \text{ m}^3\text{s}^{-1}$). Water surface slopes were interpolated to range from 0.0057 at base flow (bed gradient of the monitoring reach) to 0.0030 at $5 \text{ m}^3\text{s}^{-1}$ as the downstream riffle crest asserted increasing influence on flows in the monitoring reach. Average water surface slope decreases further to 0.0023 by $20 \text{ m}^3\text{s}^{-1}$ and remained steady until overtopping ($32 \text{ m}^3\text{s}^{-1}$) after which it increases fractionally with flow depth to 0.0025 at $42 \text{ m}^3\text{s}^{-1}$, presumably to facilitate floodplain drainage. Figure 8 reveals that the point scatter associated with impacts against shear stress is very similar to that previously obtained relating impacts to discharge (Figure 7) but with slightly less explanation ($R^2 = 0.33$, versus 0.38 for discharge). More clearly even than discharge, there is the implication of morphology-related ‘steps’ in the relation between tractive force and impacts and this may well be related to sediment dynamics on the falling limb of the hydrograph (see below).

Figure 8 near here

Recent flume tests suggest the 'Benson-type' impact plate is capable of detecting bedload transport to a minimum grain size of somewhere below 12 mm (R. Carrillo/P. Downs, *unpublished data*, I. Benson, *unpublished data*). Figure 9 indicates that the threshold for routinely recording impacts begins between 3–5 m³s⁻¹, with approximately 0.1% of the total impacts are recorded by flow in the 3–4 m³s⁻¹ category compared to a cumulative total of 0.04% for lower flows. A mid-point threshold discharge of 4 m³s⁻¹ corresponds closely to grain size thresholds of 9–12 mm based on the critical shear stress required for entrainment (see Soar and Downs, *in preparation*), leading us to conclude that the minimum grain size recorded is ~10 ± 2 mm. In the context of Figure 2, the plates are thus potentially capable of recording >50–60% of the particle sizes present in the bulk bed material of the lower Avon.

Figure 9 near here

In the absence of a uniform rating relationship between fluvial drivers (discharge, shear stress) and sediment transport activity as represented by impact counts, data scatter implicates the role of other factors which, if not related to experimental or instrument influences, must reflect both the stochastic nature of bedload transport processes and variations in sediment supply either as a consequence of grain-grain interactions, local supply sources or routing of more distant catchment supplies.

Event-based time series: supply-influenced hysteresis and inter-event variability

The ability of passive sensors to record bedload transport data for extended periods provides a field data set with a resolution typically reserved for laboratory studies, for instance, in allowing study of coarse bedload transport variability during multiple

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events (see also Whitaker and Potts, 2007). Data in Figures 10 (for a large overbank storm event) and 11 (marginally overbank events), aggregated to hourly intervals for clarity, are characteristic of a consistent pattern of hysteresis recorded during storm events. In each case, bedload transport spikes abruptly as discharge rises (but the threshold discharge is different in each case – as Turowski *et al.*, 2011) before decreasing significantly during the peak flows. A second bedload spike occurs during falling in-bank discharges and, in each of these examples, provides both a larger and longer-lived peak, accounting for the majority of coarse bedload transport activity.

Figure 10 near here

Conceivably, the initial spike in activity relates to sediment released by rupturing of the upstream gravel bar armour as flows increase (Kuhnle, 1992) or the local availability of easily-entrained material (Habersack *et al.*, 2001; Mao *et al.*, 2014). It may also represent an abrupt change to phase two transport wherein the weak armour of the Avon’s riffles enable a relatively narrow range of discharges to bring the majority of particles into motion (Bathurst, 2007). The spike on the receding limb may reflect local supply enhancements generated by bank mass failures as saturated river banks lose their confining pressure of water (Simon *et al.*, 2000; Simon and Collison, 2002) – banks upstream of the study reach are laterally active and contain substantial basal gravel deposits. Alternatively, supply enhancements may reflect time-lagged routing of flood-driven bedload sheets (Recking *et al.*, 2009) into the lower reaches of the Avon from further upstream. Reduction in coarse bedload transport during the flood peak raises the possibility of significant supply exhaustion following limited disruption to the surface armour (Andrews and Erman, 1986; Wilcock and DeTemple, 2005). There is, of course, the possibility of intensive

but unrecorded transport of bedload finer than the 10 mm detection threshold during this period. Note also the secondary peaks in Figures 10 and 11, potentially indicative of discrete bedload sheets passing over the impact plate. Such peaks may also result from grain-size and transport-style dependencies in impact plate recording efficiency (Rickenmann and McArdell, 2007; Turowski and Rickenmann, 2009; Rickenmann and Fristischi, 2010), as reviewed earlier. The prospect that peak flow impact counts are reduced because of displacement in the main track of sediment transport away from plate IP1 is largely discounted on the basis of results from neighbouring impact plates in the next section.

The study period produced 48 discrete flow events averaging 32 hours in duration. Twenty-one were categorised as sub-‘bar full’ events ($<20 \text{ m}^3\text{s}^{-1}$, average duration 24.2 hours), seven as over-bar but in-bank events ($21\text{--}32 \text{ m}^3\text{s}^{-1}$, 32.6 hours) and twenty as overbank events ($>32 \text{ m}^3\text{s}^{-1}$, 41.1 hours). Characterising each event using the hysteresis index (HI) of Aich *et al.*, (2014, following Lawler *et al.*, 2006) suggested that there were half as many clockwise events ($n=14$) as anti-clockwise ($n=28$), and that the mode of hysteresis becomes predominantly anti-clockwise in the longer overbank events (Table 1). It appears that in these events, the dominant source of sediment pulsing is likely to involve upstream bank failure and supplies routed from non-local sediment sources whereas, for in-bank events, pulses derived from surface armour disruption riffles are equally as likely to form the dominant pulse.

Table 1 near here

In addition to intra-event hysteresis, the impact plate data also reflect considerable inter-event variability in bedload transport intensity. Here, the clearest example of inter-event variability occurs either side of the record flood event where two events

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388 peaking at approximately $30 \text{ m}^3\text{s}^{-1}$ and of similar duration produce markedly different
389 impact counts (Figure 11). Far greater coarse bedload is apparently transported
390 following the record flow, presumably reflecting the availability of large volumes of
391 catchment-supplied sediment following the 7th July event (see also Lenzi, *et al.* 2004;
392 Turowski, *et al.* 2009). Frequent high flow events during the study period constrain
393 our ability to examine this trend further, but the logicity of increased sediment
394 availability following a large flow event suggests genuine supply-related transport
395 fluctuations rather than an artefact of the recording device.

396 **Figure 11 near here**

397 **Selective path transport**

398 In all but the smallest of rivers (or where vast resources are available, e.g., Hildale
399 *et al.*, 2015) portable bedload samplers or traps monitor only part of the active bed,
400 irrespective of the type of device. Here, the monitoring reach was chosen largely to
401 exploit the apparent central channel focus of bedload transport, and impact plate IP1
402 was situated accordingly. However, bedload transport is known to involve
403 morphology-dependent partial width travel paths (Dietrich and Smith, 1984; Parker
404 and Andrews, 1985; Julien and Anthony, 2002; Bunte, *et al.*, 2006) that shift laterally
405 with discharge and as the channel migrates, and so installation of three additional
406 impact plates in December 2012 (see Figure 4) enabled examination of the spatio-
407 temporal attributes of continuous monitoring of bedload impacts.

408 Figure 12 indicates that there is indeed considerable lateral and longitudinal
409 variability in the impact counts and that the relative intensity of impacts changes
410 during events. Removing the zero-count data, the central plate IP1 is by far the best
411 explained by discharge (Table 2) followed distantly by IP3 (right of centre) which

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3 412 actually records 20% more impacts but significantly time-lagged with respect to
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5 413 discharge. The left of centre plate IP2 records only 9% of the impacts of IP3 and
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7 414 with little relation to flow magnitude, indicating a significant asymmetry in bedload
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9 415 transport across the channel. IP4, installed centrally but 10 m upstream of IP1 has
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11 416 performance characteristics similar to IP2. Laterally, the channel cross-section is
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13 417 slightly shallower and coarser-grained towards the left bank (IP2) whereas the right
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15 418 channel is slightly deeper and finer-grained at the surface. It appears that a minority
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17 419 of very coarse bedload is transported across IP2 (which is progressively becoming
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19 420 the head of the downstream point bar) and, as flood events wane, there is an
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21 421 increasingly diagonal flow path transferring finer gravels towards IP3. Indeed,
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23 422 impact rates at IP3 appear to show no increase with rising discharge, rather they
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25 423 increase at the near-cessation of transport across IP1 illustrating a flow-dependent,
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27 424 and quite probably size-selective, lateral variability in coarse bedload transport. The
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29 425 pattern of response apparently confirms the focus of bedload transport along the
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31 426 central maximum velocity filament which veers slightly from river left to river right
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33 427 through the monitoring reach, passing closer to IP3 than to IP2 and largely by-
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35 428 passing IP4 upstream. This path is becoming more diagonal as the upstream
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37 429 meander bend migrates into the left bank, making IP4 increasingly distant from the
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39 430 bedload track. Difference in impacts between IP3 versus IP2, and IP1 versus IP4
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41 431 are thus readily explained but reinforce the critical importance of sensor location.
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48 432 Combining impact counts from the various plates for the 4.5 months of (winter)
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50 433 monitoring improves the explanation achieved from 41% to 49% (three lateral plates)
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52 434 or 51% (all four plates). This is interpreted to indicate that (i) modest improvements
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54 435 in tractive force-based explanations for bedload variability can be achieved with the
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56 436 use of additional plates, (ii) *ca.* 50% of the impact variability is still unaccounted
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3 437 using the array of plates emphasizing the importance of fluctuating supply dynamics
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5 438 and the inherently stochastic behaviour of sediment in transport, and (iii) plate IP1
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7 439 does provide the most representative account of transport-related impact dynamics
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9 440 during the study period.

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12 441 **Figure 12 and Table 2 near here**

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19 443 **Discussion: insights into lowland bedload dynamics**

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22 444 Passive sensors such as seismic impact plates offer a high-resolution window into
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24 445 field-based continuous measurements of bedload dynamics (initiation, cessation,
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26 446 intensity of transport), but they bring with them new challenges in data interpretation.
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28 447 Here, in a downstream reach of a flashy, gravel-bedded river system, the primary
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30 448 impact plate (IP1) continuously recorded data during the wettest 12 months on
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32 449 record (Figure 5) with only one data gap when flows were consistently too high to
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34 450 safely retrieve the plates for data download. The bedload transport dynamics
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36 451 recorded here as impacts reflect four categories of competing controls. These
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38 452 include experimental artefacts related to plate performance and monitoring design,
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40 453 tractive force limitations on the size and volume of material in transit, inherent short-
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42 454 term stochasticity in the relation of bedload discharge to shear stress resulting from
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44 455 granular controls on transient bed forms (e.g., passage of bed load sheets), and the
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46 456 ability of local and more distant sediment sources to provide supplies sufficient to
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48 457 meet volumetric transport potential.

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53 459 Regarding experimental factors, the plates appear to reliably record movement of
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55 460 sediment ≥ 10 mm (Figure 9, corroborated by unpublished performance testing) and

the 2.5 minute data-logging period avoided sensor saturation until the flood of record and repeated high flow events thereafter increased sediment supply (Figure 6).

While such sensor saturation inevitably limits insights into bedload dynamics in the very highest flows, here saturation occurred predominantly in just one event, and may represent a minor overall precision consideration relative to other potential factors such as multiple impacts from rolling particles, single counts where multiple particles strike the plate simultaneously (Beylich and Laute, 2014), recording variability related to the particle's striking velocity (Rickenmann and McArdell, 2007, 2008), and size-dependent recording efficiency of the plate (Rickenmann *et al.*, 2012). Parallel matters of accuracy and representativeness exist with other forms of bedload monitoring (Bunte *et al.*, 2008; Bunte and Abt, 2009) and require further research into impact plate design and performance. The lack of plate burial (or exhumation) following flood events may indicate that the locally-steep monitoring reach acts as a 'flush through' reach in terms of sediment connectivity (*sensu* Hooke, 2003, her Figure 3). The ability to compare performance between plates suggested that the dynamics of coarse bedload transport in the study reach were elucidated by the impact counts rather than any overwhelming attribute of plate positioning. These final two concerns highlight the need for both careful site selection and an array of sensors in all but the narrowest of channels.

To explore the extent that bedload dynamics reflect transport, supply and stochastic factors, impact counts were integrated over discrete flow events using total volumetric discharge above the $4\text{m}^3\text{s}^{-1}$ detection threshold as a surrogate for the total available energy for sediment transport during each event. As there is evidence that a strong relationship exists both between event flow volume and transported sediment mass (Rickenmann 1997, 2001, Rickenmann and McArdell, 2007), and

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3 486 between transported sediment mass and total event impacts (Rickenmann *et al.*,
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5 487 2012), a plot of total impacts versus effective flow volume describes a surrogate
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7 488 relationship between event impacts and event bedload mass. The result (Figure 13)
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9 489 indicates that 74% of variance was explained by this event-based summary of
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11 490 transport potential in comparison to the 38% of instantaneous variance (Figure 7).
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13 491 Unsurprisingly, the implication is that moving the time base from 5-minute intervals to
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15 492 the event average of 32 hours promotes the role of tractive forces in controlling
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17 493 bedload transport at the expense of stochastic and intra-event supply factors. The
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19 494 remaining unexplained variance may relate primarily to sediment supply differences
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21 495 between events and the limitations of a single impact plate in representing cross-
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23 496 sectional bedload transport. In comparison, Rickenmann *et al.* (2012) achieved 91%
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25 497 explanation when directly comparing event impacts to event sediment mass in the
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27 498 steep, 0.7 km² Erlenbach stream (their Figure 6b). Such extra explained variance
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29 499 presumably arose from having an impact plate array spanning the entire channel
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31 500 cross-section, more uniform bedload dynamics resulting from a small, steep
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33 501 catchment, and the direct use of sampled sediment mass (rather than our surrogate
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35 502 of 'effective flow volume') that intrinsically accommodates inter-event supply
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37 503 variability.
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44 504 **Figure 13 near here**

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46 505 Aggregating the data further, a surrogate measure of 'effective discharge' (Wolman
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48 506 and Miller 1960; Andrews, 1980) was derived by substituting recorded impacts for
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50 507 estimated bedload mass in 1 m³s⁻¹ discharge increments (Figure 14: Soar and
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52 508 Thorne 2001 method; see Biedenharn *et al.*, 2000 and Soar and Thorne, 2011 for
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54 509 reviews of methods). Over long timeframes, effective discharge potentially provides
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56 510 a summary definition for the dynamic equilibrium of river systems in terms of a quasi-
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3 511 steady relationship between the prevailing sediment transport regime and a resultant,
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5 512 stable, channel morphology (examples in Whiting *et al.*, 1999; Emmett and Wolman,
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7 513 2001; Goodwin, 2004; Orndorff and Glonek, 2004; Torizzo and Pitlick, 2004;
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9 514 Crowder and Knapp, 2005; Doyle *et al.*, 2005; Doyle and Shields, 2008; Lenzi *et al.*,
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11 515 2006). By inference, the result here potentially indicates the dynamic 'state' of the
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13 516 lower Avon during an extremely wet year. Figure 14 indicates a peak from 13 to 15
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15 517 m^3s^{-1} reflecting the dominance of this discharge range for coarse sediment transport.
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17 518 It will additionally reflect some systematic offset caused by substituting impact
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19 519 frequency for bedload mass whereby the volumetric influence of larger particles on
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21 520 total load is underrepresented. It may also reflect bias in impact plate performance if
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23 521 there is an optimum flow range for recording plate impacts. A cumulative plot of
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25 522 impacts denoting the break point of several cross-sectional stages confirms that the
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27 523 effective discharge, depicted by the inflection point in the curve of cumulative
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29 524 impacts, occurs at events far less than bankfull (Figure 15). This result reflects the
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31 525 exceptionally frequent mobilisation of coarse gravels during this wettest year on
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33 526 record, but is probably not representative of multi-decadal discharge effectiveness.
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39 527 Figure 14 near here

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45 529 In interpreting effective discharge as a summary measure of channel-forming
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47 530 processes, a focal concern exists for the magnitude of the effective discharge
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49 531 relative to bankfull flows. Whereas many studies have commented on the
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51 532 equivalence of the two measures (*e.g.*, Wolman and Miller, 1960; Leopold *et al.*,
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53 533 1964; Andrews, 1980; Carling, 1988; Andrews and Nankervis, 1995; Pitlick and Van
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55 534 Steeter, 1998; Torizzo and Pitlick, 2004; Powell *et al.*, 2006), others have argued
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535 that the relative measure of effective discharge may be highly variable (Williams
536 1978) and range from the minimum (Watson *et al.*, 1997, Crowder and Knapp, 2005)
537 to the maximum flow class (e.g., Wolman and Gerson, 1978; Bunte *et al.*, 2014).
538 Consequently, river morphology may be better characterised by several modal
539 discharges responsible for different component parts of the morphology or sediment
540 transport processes (e.g., Pickup and Warner 1976; Phillips, 2002; Mueller *et al.*,
541 2005; Ryan 2005; Lenzi *et al.*, 2006; Surian *et al.*, 2009) or by a range of flows (Soar
542 and Thorne 2011). Overall, effective discharge results from the interplay of four
543 environmental factors including the prevailing hydroclimate, channel characteristics,
544 dominant bed material grain size and characteristics of sediment supply, filtered
545 through three procedural issues related to the bedload sampling technique, the time
546 base of discharge measurement and the size of increment used to sub-divide the
547 flow frequency distribution. As such, the ‘position’ of the effective discharge within
548 the spectrum of all sediment-transporting flows will reflect several dominant factors
549 working in combination.

550 The influence of hydroclimatic factors determining the prevailing flow regime is
551 reflected primarily in the variance and skewness of flow frequency. Streams with low
552 flow variance and positively skewed distributions promote the role of smaller
553 discharges below bankfull as effective (Benson and Thomas, 1966; Harvey, 1969;
554 Pickup and Warner, 1976; Nolan *et al.*, 1987; Whiting *et al.*, 1999; Orndorff and
555 Glonek, 2004), especially where sediment is highly mobile. Conversely, highly
556 variable flow regimes associated with smaller drainage basins (Andrews, 1980;
557 Andrews and Nankervis, 1995) or more ephemeral conditions (Wolman and Gerson,
558 1978; Werrity, 1997; Downs *et al.*, 2013) promote the role of far rarer events. While
559 the Avon has a natural flashy flow regime, overall flow variability is low. The central

95% of long-term daily mean flows range only from 0.4–15 m³s⁻¹ (Figure 5) reflecting frequent precipitation events. During our study period, the same range was 1.4–30 m³s⁻¹ implying a similar variability but consistently higher flows likely to provide bed mobility and thus providing a mechanism for effective discharge at flows far less than bankfull.

The role of grain size in effective discharge has been used since the concept's inception (Wolman and Miller 1960) to distinguish the relatively lower effective discharge in sand-bedded channels with low thresholds for grain mobility, from that in gravel-bedded rivers where effective discharge is generally closer to (or above) bankfull. In the latter case, bed armouring and particle hiding favour equal mobility of bedload over selective entrainment and typically result in steep rating curves with high regression exponents that increase the magnitude of the effective discharge (Emmett and Wolman, 2001; Vogel *et al.*, 2003; Barry *et al.*, 2008; Quader and Guo, 2009; Soar and Thorne, 2011; Bunte *et al.*, 2014). The Avon, although coarse grained, has a significant fraction of sediments just above the instrument detection range – about 20% of subsurface and 10-25% of surface particles are in the range 10-20 mm (Figure 2). With apparently limited bed armour and frequent events above the mobilisation threshold in this very wet year, there was a progressive increase in bedload transport intensity in flows beyond the detection threshold (Figure 9), such that detectable sediment may have been mobile in approximately two of every three days (Figure 5, *cf.* Lenzi *et al.*, 2006).

Above the mobilisation threshold, there is clearly a steep component to the 'impact rating curve' in the range 10-20 m³s⁻¹ illustrated by the 95th percentile of transported particles in Figure 7. This may represent a change from size selective partial mobility to complete bed mobility, except that here such conditions are happening in

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3 585 flows approaching ‘barfull’ rather than approaching bankfull (*cf.* Mueller *et al.*, 2005).
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5 586 For flows in excess of barfull the linear rating breaks down rapidly so that the overall
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7 587 power law in Figure 7 has a low exponent compared, for instance, to those in
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9 588 mountain streams (1.6, here, for impacts, versus 3.3–18.3 for load in Bunte *et al.*,
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11 589 2014). Reasons for the breakdown in bedload rating in flows above barfull may
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13 590 relate to issues of local or catchment sediment supplies. For example, if the
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15 591 coarsest particle sizes are already in motion in moderate flood flows and no coarser
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17 592 supplies exist to proportionately augment yields in higher (and overbank) flows,
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19 593 transport rates will be well below theoretical maximums (Bunte *et al.*, 2014).
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21 594 Conceivably this is important here because of the low recurrence interval (RI, =1.0)
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23 595 of overbank flows and a study period that included 20 overbank events and flows up
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25 596 to 230% of the statistical bankfull discharge, Q1.5 (~53 m³s⁻¹). With saturation of
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27 597 impacts potentially occurring at discharges as low as 10 m³s⁻¹ (Figure 7), higher
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29 598 flows potentially face significant supply limitations, apparently depicted in Figure 7,
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31 599 especially before catchment supplies are routed through the reach. This may partly
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33 600 explain the preponderance of negative hysteresis in large events (Figures 10, 11;
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35 601 Table 1).
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41 602 Clearly, the *overall* impact rating exponent (1.6) here is lower than would have been
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43 603 obtained using rated bedload because the volumetric mass of coarser sediments
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45 604 transported in larger flows is not accommodated. But both the particle size
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47 605 distribution (high proportion of ‘finer’ bed material close to the plate detection limit)
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49 606 and sediment supply factors (markedly lower impacts above barfull stage) both also
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51 607 promote a relatively low effective discharge. Further, the channel character (pool-
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53 608 riffle, actively meandering, weakly armoured bed, high flow water surface slope
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55 609 ~0.0025) significantly separates the Avon from steeper channel types argued to
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3 610 implicitly favour effective discharge at flows greater than bankfull (Lenzi *et al.*, 2006;
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5 611 Bunte *et al.*, 2014).
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8 612 Beyond physical factors, several procedural factors potentially influence the 'position'
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10 613 of effective discharge relative to bankfull flow. Instrument factors include the
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12 614 prospect that Helley-Smith samplers significantly underestimate the steepness of the
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14 615 bedload rating curve relative to bedload traps (Bunte *et al.*, 2014). The sensitivity
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16 616 and extended deployment periods of impact plate measurements nullify similar
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18 617 influences, but systematic underrepresentation of particles saltating over the plate
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20 618 and moving in clusters remain as potential issues. Second, regarding time period
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22 619 discharge intervals, the use of 15-minute flow data interpolated to 5 minutes to
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24 620 match the resolution of impact measurements is appropriate for such a flashy river.
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26 621 It avoids inherently skewing effective discharge towards smaller flow increments
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28 622 which can occur using longer time steps (e.g., daily mean flows) if they mask shorter
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30 623 periods of marked grain mobility (Biedenharn *et al.*, 2000). Third, in relation to the
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32 624 most appropriate discharge class interval (Sichingabula, 1999; Goodwin, 2004;
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34 625 Crowder & Knapp, 2005; Lenzi *et al.*, 2006), the use of short time period discharges
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36 626 in conjunction with a small discharge increment discretised from the cumulative
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38 627 discharge plot (as here) should produce a reasonably smooth distribution of bedload
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40 628 (or impacts) and precise estimate of effective discharge. It will also tend to favour a
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42 629 multi-increment *range* as the effective discharge (Soar and Thorne, 2011), as
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44 630 evidenced in Figure 14.
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51 631 There is a clear discord here between the surrogate effective discharge from
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53 632 bedload impacts ($13\text{--}15\text{ m}^3\text{s}^{-1}$) and the statistical bankfull discharge ($Q_{1.5} \approx 53\text{ m}^3\text{s}^{-1}$)
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55 633 (Figure 15). Such discordance is not uncommon (e.g., Pickup and Warner, 1976;
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57 634 Orndorff and Glonek, 2004; Soar and Thorne, 2011) and deconstructing the effective
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635 discharge process provides justification for the relatively low value. In summary, the
636 result is likely attributable to: i) the numerous bar-topping and high in-bank events
637 during the wet year that maintained a comparatively loose bed material that was
638 easily entrained (Reid *et al.*, 1985); ii) an abundant supply of finer gravels capable of
639 mobilisation in low flows coupled with evidence of periodic exhaustion during
640 extreme flows that both reduce the rating exponent (Bunte *et al.*, 2014); iii) a pool-
641 riffle channel character and a relatively low magnitude of flow variability that are
642 inherently suited to lower effective discharges, and; iv) an omission of procedural
643 filters (*e.g.*, insensitive instrumentation, long time period discharge interval) that
644 might intrinsically promote a higher effective discharge. Perhaps surprisingly, given
645 the frequent high flow events in the study period, there is no evidence for multiple
646 effective discharges related to 'nested channel architectures' (Dollar 2002; Lenzi *et*
647 *al.*, 2006). While the sub-barfull effective discharge of <1-year RI seems highly
648 indicative of 'bedform maintaining' conditions, there is almost no bimodality indicated
649 in Figure 14. It may be that the high frequency of moderate flood events during the
650 year (Figure 6) negated the prospect of identifying a clear secondary peak but that
651 such a peak might show more clearly during 'average' flow years.

652 Beyond effective discharge, the resolution provided by the impact plate data
653 illustrates competing facets of gravel-bed river dynamics. Frequent high flow and
654 rapidly waning events in conjunction with the progressive increase in sediment
655 transport capacity (Figure 9) suggest largely transport-limited conditions at the event
656 scale (Figure 13) whereas, at the 'near instantaneous' level, hysteretic pulses of
657 coarse sediment (Table 1) moderate the statistical explanation achieved between
658 discharge and impact counts (Figure 7), suggesting strongly supply-dependent
659 conditions. Conceivably, during this exceptionally wet year, bedload transport in the

Avon may be characterised as 'pulse-limited' rather than either fully transport- or supply-limited: there was a seemingly unlimited *frequency* of sediment pulses but not an unlimited sediment *supply* during each pulse.

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664 Conclusion

Impact plates, deployed to monitor coarse bedload transport at near-instantaneous periods, have apparently provided some novel insights into the functioning of the downstream reach of a gravel-bedded river, and help counteract Gray et al.'s (2010c, p.209) concern that "Progress in knowledge about bed load-transport processes is retarded for want of more reliable, accurate, and temporally dense bed load datasets." Data aggregation into 5-minute, event and annual timescales during this exceptionally wet twelve month period allowed a comparative interpretation of bedload dynamics with implications for understanding the relative importance of transport-limited and supply-limited behaviours. Transport-limitations appear to account for only about 40% (single plate) to 50% (three plates) of the impact count variability over 5-minute intervals, while event-based time series illustrated apparently significant intra-flood supply variations with the regular occurrence of rising- and falling-limb spikes in coarse bedload transport and a pattern related to the event magnitude. Aggregating the primary plate counts over event timescales (here averaging 32 hours) raised explained variability to 74%. A $1 \text{ m}^3\text{s}^{-1}$ increment magnitude-frequency analysis of the flows resulted in a typical frequency distribution, albeit with the effective discharge peaking at flows far closer to 'bar full' than morphological bankfull. Beyond environmental and procedural factors, one implication is that while estimates of effective discharge tacitly assume a primary

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684 dependency of coarse bedload transport on tractive force limitations, high-resolution
685 measurements indicate that the distribution actually results from statistical averaging
686 of considerable intra-event supply-limiting factors. Clearly, such a prospect
687 demands investigation in other environments and under more typical flow regimes.

688 More generally, the use of a single or limited array of impact plates appears to have
689 some merit in understanding the bedload dynamics of a gravel-bedded river, even
690 when installed across a 12 m active bed width that allows far less experimental
691 control than the majority of applications to date. Further flume tests are required to
692 establish the true performance dynamics of these and similar instruments but, in
693 comparison to the expected dynamics of coarse bedload transport, the results here
694 appear comparable with other commonly-utilised portable methods of bedload
695 monitoring. Issues of achieving representative cross-stream sampling of bedload is
696 shared with other approaches, while the capacity for robust and unobtrusive
697 deployment over extended time periods without concerns for reaching sampling
698 capacity maximises the approach's cost-effectiveness in labour terms. Overall, the
699 capacity for such portable devices to provide large volumes of high-resolution data
700 does truly suggest an element of 'liberty' in bedload monitoring, while the low cost of
701 the instruments relative to permanent monitoring installations indicates some
702 potential for better 'equality' in long-term bedload monitoring . It perhaps remains
703 only for the co-operation of scientists in replicating, validating and calibrating impact
704 plate data to provide the 'fraternity' necessary to prove Gray *et al.*'s (2010b)
705 assertion that surrogate devices provide a revolutionary concept in fluvial
706 sedimentology, and an important first step in this regard has already been achieved
707 (Rickenmann *et al.*, 2014).

For the River Avon, these detailed insights into coarse bedload dynamics were achieved during an exceptionally wet year that is arguably unrepresentative of typical conditions. However, lichenometry indicates that flood events were far more widespread in the Dartmoor region in the decades immediately pre-dating flow gauging records (Foulds *et al.*, 2014). Routine monitoring of bedload using impact plate arrays could form a cost-effective route for better understanding the dynamics of short-term fluvial activity during such wet periods, and thus contribute in managing the risks associated with more frequent extreme events, whether resulting from natural climate cyclicity or anthropogenically-enhanced climate change.

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Table and Figure Captions

- Table 1: Indication of direction of hysteresis in 48 discrete flow events during the study period.
- Table 2: Impact count properties of Impact Plates 1 to 4, singly, in cross-sectional array (IP1-IP3) and in total (IP1-IP4).
- Figure 1: a) Catchment of the River Avon, Devon, UK showing location of study site and gauging station; b) aerial view of study reach (source: Google Earth)
- Figure 2: Particle size distribution of surface and bulk samples from the study reach by Wolman count and mass, respectively.
- Figure 3: ‘Benson-type’ impact plate: a) topside view shown mounted to paving slab b) underside showing recessed accelerometer, data logger, and connector (yellow) for data download
- Figure 4: Schematic layout of impact plates in the study reach. IP1 was installed in late April 2012, the other plates in December 2012. Arrangement of plates in monitoring reach
- Figure 5: Flow duration curves on mean daily flows for the lower Avon using 36 years of flow gauging at Loddiswell (NFRA station 46008: 1971-81; 1991-2013), illustrating the extreme wetness of the study period. Dashed straight lines indicate a banded threshold for coarse (≥ 10 mm) particle transport (see Figure 9) and suggest coarse particle transport in $\approx 68\%$ of days (using $4 \text{ m}^3 \text{ s}^{-1}$ threshold) during the study period rather than in $\approx 29\%$ of days from the long term record.
- Figure 6: Time series of gauged discharge and impacts as recorded by Impact Plate 1 from late April 2012 – early May 2013. Impacts are aggregated to 5-minute intervals (= 2 x 2.5 minute logging periods) with a maximum of

1069 510 counts in each of 92,284 periods. One data gap in late November
 1070 occurs where safe retrieval of the plates was impossible. Discharge
 1071 records are interpolated between 15-minute 'instantaneous' gauging
 1072 records.

1073 Figure 7: Instantaneous discharge versus 5-minute impact count totals for 27,850
 1074 'non-zero' records during the study period for Impact Plate 1. Data
 1075 saturation occurs in 139 (0.5%) of the total non-zero impact periods,
 1076 mostly during one event (see text). Indicative 'weighted' percentiles
 1077 highlight the variability with discharge, based on a moving window through
 1078 10% of the dataset and a Gaussian kernel smoothing algorithm to weight
 1079 points according to proximity to the centre of the window.

1080 Figure 8: Local bed shear stresses for the water column above Impact Plate 1
 1081 versus 5-minute impact count totals for the study period. Percentiles are
 1082 calculated as per Figure 7.

1083 Figure 9: Discharge increments ($1 \text{ m}^3 \text{ s}^{-1}$) versus percentage of total bedload
 1084 impacts for Impact Plate 1 illustrating a threshold for appreciable
 1085 recording of impacts at approximately $4 \text{ m}^3 \text{ s}^{-1}$ (range of $3\text{--}5 \text{ m}^3 \text{ s}^{-1}$).

1086 Figure 10: Intra-event variability in bedload transport intensity illustrated by impact
 1087 counts (aggregated to one-hour periods for clarity) versus discharge for a
 1088 large overbank flow event on 20/12/12. Here, impacts rise sharply as the
 1089 discharge approaches bankfull and spike again after flows drop close to
 1090 bar full. Significantly more impacts occur on the receding limb.

1091 Figure 11: Inter-event variability in bedload transport intensity illustrated by impact
 1092 counts (aggregated to one-hour periods for clarity) versus flows for two
 1093 similar events occurring either side of the flood of record (7/7/12). The

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3 1094 plots show similar patterns of intra-event impact spiking but note
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5 1095 (compare secondary y-axes) the far greater number of impacts in the
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7 1096 second event ($\approx 27,500$ event total impacts) than the first ($\approx 6,000$ event
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10 1097 total impacts).
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12 1098 Figure 12: Time series of gauged discharge versus the four-impact plate array (See
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14 1099 Figure 4) aggregated to 5-minute intervals from late December 2012 –
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16 1100 early May 2013. Plate 1 is plotted between plates 2 (river left) and 3 (river
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18 1101 right) to facilitate visual comparison. Note that plate 1 and plate 4 are
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20 1102 both in centre channel. Comparisons of the records is indicated in Table
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22 1103 2.
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25 1104 Figure 13: Event total ‘excess’ discharge (*i.e.*, discharge above the $4 \text{ m}^3\text{s}^{-1}$ threshold
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27 1105 for impact recording) versus event total bedload impacts for 48 discrete
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29 1106 events (peak discharges $6\text{--}124 \text{ m}^3\text{s}^{-1}$) during the study period. Note
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31 1107 improvement in explained variability versus the ‘instantaneous’
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33 1108 comparison in Figure 7.
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36 1109 Figure 14: Magnitude-frequency analysis of total bedload counts at $1 \text{ m}^3\text{s}^{-1}$
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38 1110 increments for Impact Plate 1 during the study period, illustrating an
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40 1111 effective discharge equivalent measure for coarse bedload transport from
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42 1112 13 to $15 \text{ m}^3\text{s}^{-1}$.
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45 1113 Figure 15: Cumulative magnitude-frequency analysis of total bedload counts at 1
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47 1114 m^3s^{-1} increments for Impact Plate 1, illustrating changes in curvature as
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49 1115 flows inundate the ‘upper stage’ of the channel as they exceed ‘barfull’
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51 1116 ($\approx 20 \text{ m}^3\text{s}^{-1}$), and again as flows exceed morphological bankfull ($\approx 32 \text{ m}^3\text{s}^{-1}$),
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53 1117 but that the primary inflexion at the point of effective discharge (“ Q_{eff} ” $\approx$
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55 1118 $14 \text{ m}^3\text{s}^{-1}$) occurs at much lower flows during this extremely wet year.
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1119 Table 1

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Type of event	Peak discharge m^3s^{-1}	Hysteresis			Total
		Clockwise	No hysteresis ($-0.1 < \text{HI} < +0.1$)	Anticlockwise	
Sub-barfull	<20	8	4	9	21
Bar-to-bankfull	21-32	4	0	3	7
Overtopping	>32	2	2	16	20
Total		14	6	28	

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1122 Table 2

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	Impact Plate					
	IP1	IP2	IP3	IP4	IP1-IP3	IP1-IP4
Number of non-zero periods	13,180	5,795	20,071	4,998	21,733	21,768
Total counts	651,092	72,331	783,458	68,527	1,506,881	1,575,408
R ² for power relationship of discharge vs. non-zero impacts	0.41	0.10	0.18	0.13	0.49	0.51

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