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1

2 **Spatial variations in surface sediment structure in riffle-pool sequences: a**
3 **preliminary test of the Differential Sediment Entrainment Hypothesis (DSEH)**

4

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12 **Abstract**

13 Riffle-pool sequences are maintained through the preferential entrainment of sediment
14 grains from pools rather than riffles. This preferential entrainment has been attributed
15 to a reversal in the magnitude of velocity and shear stress under high flows; however
16 the Differential Sediment Entrainment Hypothesis (DSEH) postulates that differential
17 entrainment can instead result from spatial sedimentological contrasts. Here we use a
18 novel suite of *in-situ* grain-scale field measurements from a riffle-pool sequence to
19 parameterise a physically-based model of grain entrainment. Field measurements
20 include pivoting angles, lift forces and high resolution DEMs acquired using
21 Terrestrial Laser Scanning, from which particle exposure, protrusion and surface
22 roughness were derived. The entrainment model results show that grains in pools have
23 a lower critical entrainment shear stress than grains in either pool exits or riffles. This
24 is because pool grains have looser packing, hence greater exposure and lower pivoting
25 angles. Conversely, riffle and pool exit grains have denser packing, lower exposure
26 and higher pivoting angles. A cohesive matrix further stabilises pool exit grains. The
27 resulting predictions of critical entrainment shear stress for grains in different subunits
28 are compared with spatial patterns of bed shear stress derived from a 2D
29 Computational Fluid Dynamics (CFD) model of the reach. The CFD model predicts
30 that, under bankfull conditions, pools experience lower shear stresses than riffles and
31 pool exits. However, the difference in sediment entrainment shear stress is sufficiently
32 large that sediment in pools is still more likely to be entrained than sediment in pool
33 exits or riffles, resulting in differential entrainment under bankfull flows.
34 Significantly, this differential entrainment does not require a reversal in flow
35 velocities or shear stress, suggesting that sedimentological contrasts alone may be
36 sufficient for the maintenance of riffle-pool sequences. This finding has implications

37 for the prediction of sediment transport and the morphological evolution of gravel-bed
38 rivers.

39 **Keywords**

40 Entrainment, Sediment packing, Riffle-pool, Terrestrial Laser Scanning, Bed shear
41 stress,

42 **1. Introduction and theory**

43 The surface of gravel-bed rivers represents an important control on flow resistance
44 (Smart *et al.*, 2004), boundary layer dynamics (Buffin-Belanger *et al.*, 2006), and the
45 entrainment and transport of bed material (Hodge *et al.*, 2007). Gravel surfaces are
46 also the interface between bulk channel flow and shallow hyporheic flows (Harvey
47 and Bencala, 1993), control the infiltration of fine sediments into the bed (Frostick *et*
48 *al.*, 1984; Sear *et al.*, 2008), and provide a substrate for a range of biota (Johnson *et*
49 *al.*, 2009; Johnson *et al.*, 2010; Jones *et al.*, 2011; Kemp *et al.*, 2011).

50

51 Much research has explored the spatial and temporal distribution of particle sizes at
52 the bed surface; however, sediment size alone cannot fully explain the dynamics of
53 sediment transport in alluvial rivers. It is likely that the structural arrangement of
54 particles plays a critical role in causing variability in sediment transport (Jerolmack,
55 2011). Flowing water organises particles into structural groups and bed fabrics;
56 surface particles are repositioned into more stable positions within the bed by small
57 *in-situ* particle movements during periods of sub-critical and turbulent flows (Clifford
58 and Richards, 1992; Sear, 1996; Haynes and Pender, 2007), short distance movement
59 during partial transport (Sear 1996), and the formation of structural elements (e.g.
60 pebble clusters, ribs, polygons) during transport (Oldmeadow and Church, 2006).

61 Biological activity can also alter the structure of surface gravels (Johnson *et al.*,
62 2010). Hydraulic, sedimentological and bed structure contrasts are to be found across
63 a wide range of scales in gravel-bed rivers, from the presence on the bed surface of
64 individual patches of contrasting grainsize (Vericat *et al.*, 2008); through step-pool
65 and riffle-pools (Milne, 1982; Clifford, 1993; Sear, 1996) to large bar scale facies
66 contrasts (Rice and Church, 2010). Hence, there are spatial controls on entrainment
67 via structural contrasts that will influence bed mobility and the evolution of bed
68 morphology.

69

70 Riffle-pool sequences are a near-ubiquitous bed morphology of alluvial gravel-bed
71 rivers. They are characterised by strong hydraulic contrasts at long duration, low
72 magnitude flows, and a progressive equalisation or even reversal in the strength of
73 these contrasts at higher in-bank flows (Keller, 1971; Booker *et al.* 2001; Milan *et al.*,
74 2001). Whilst considerable research has focussed on the hydraulic mechanisms by
75 which riffle-pool sequences are maintained, relatively few studies have examined the
76 sedimentological and structural controls on sediment transport. This dearth of studies
77 pertains despite published evidence for distinct sedimentological contrasts between
78 individual units of the riffle-pool sequence (Lisle, 1989; Milne, 1982; Clifford, 1993;
79 Sear, 1996). Sear (1992; 1996) and Clifford (1993) independently developed a
80 hypothesis that linked near bed turbulence to the evolution of tightly packed and
81 structured surface sediments on riffles that resulted in higher critical shear stress for
82 particles on riffles compared with pool subunits. They hypothesized that these
83 differences were sufficient to maintain riffle-pool morphology. However, this
84 differential sediment entrainment hypothesis (DSEH) remains untested, meaning that

85 the relative roles of velocity reversal and sedimentological contrasts in maintaining
86 riffle-pool topography are unknown.

87

88 We present the first quantitative test of the DSEH by using new technology to
89 quantify grain-scale properties relating to grain entrainment and sediment fabric in
90 different sub-units of the riffle-pool sequence. Terrestrial Laser Scanning (TLS)
91 enables the collection of *in-situ* high-resolution information on exposed bed micro-
92 topography (Hodge *et al.*, 2009a, 2009b; Heritage and Milan 2009), providing
93 measures of surface grain size, packing and fabric, including: distribution of surface
94 elevations (distribution of surface elevation relative to grainsize provides information
95 on packing and surface rugosity/ roughness); semivariograms; grain exposure
96 (Schmeekle and Nelson, 2003; Kean and Smith, 2006) and particle alignment (Smart
97 *et al.*, 2004). In this paper we 1) use TLS data and other field measurements to
98 identify spatial variations in sediment structure through a riffle-pool sequence; 2) use
99 the field data to parameterise a modified form of the physically-based entrainment
100 model of Kirchner *et al.* (1990) in order to predict spatial variation in critical
101 entrainment shear stress; and 3) compare the predicted critical entrainment shear
102 stresses with the spatial distribution of shear stress predicted by a 2D CFD model in
103 order to assess the relative roles of sediment structure and hydraulics in causing any
104 preferential sediment entrainment.

105 **2. Methods**

106 In the methods we first outline the physically-based entrainment model that is
107 parameterised using the field data. We then present the field site and the suite of field
108 measurements that were collected. Finally, the CFD model set-up is described.

109 **2.1. Grain entrainment model**

110 In order to quantify spatial variations in critical entrainment shear stress (τ_c) between
 111 riffles, pool and pool exits, we use a modified form of a physically-based model of
 112 grain entrainment (Kirchner *et al.*, 1990). The key parameters in this model, grain
 113 size, exposure, pivoting angle and resistance to lift forces, are parameterised from the
 114 field measurements (see following sections).

115

116 At the threshold of motion the following force balance applies to a grain:

117
$$\frac{F_D + F_L}{\tan \Phi} = \frac{1}{6} m F_W \rho_s g D \quad (1)$$

118

119 where F_D and F_L are respectively the drag force and the lift force, F_W is the immersed
 120 weight of the grain, m is a multiplier of F_W that incorporates the effect of additional
 121 resistance to grain entrainment (e.g. grains being held in place by a cohesive mortar),
 122 Φ is the grain pivoting angle, ρ_s is the density of sediment (taken as 2650 kg m^{-3}), ρ is
 123 the density of water, g is the acceleration due to gravity and D is the grain diameter.
 124 The incorporation of m in equation 1 is an amendment to the equations of Kirchner *et*
 125 *al.* (1990). The model of Kirchner *et al.* (1990) calculates the shear stress that solves
 126 equation 1 through consideration of grain geometry and an assumed logarithmic flow
 127 velocity profile.

128

129 To calculate values for F_D and F_L , a relationship between flow velocity and height
 130 above the bed is also needed:

131
$$u = \sqrt{g h} \left(\frac{z}{h} \right)^{1/6} \quad (2)$$

132 where $u(z)$ is the flow velocity at height above the bed z , τ is the boundary shear
 133 stress, κ is von Kármán's constant (taken as 0.4) and z_0 is the roughness height
 134 (assumed to be $0.1D_{84}$; Whiting and Dietrich 1990). The reference height $z = 0$ is
 135 assumed to be the local mean bed elevation. Equation 2 is only applicable when $z > 0$,
 136 otherwise $u(z) = 0$. F_D is calculated as:

$$137 \quad F_D = \frac{C_D}{2} \rho u^2 W(z) \quad (3)$$

138 where $W(z)$ is the width of the grain cross-section at height z , C_D is an empirical drag
 139 co-efficient assumed to be 0.4 (Wiberg and Smith, 1985), p and e are respectively
 140 grain protrusion and exposure. F_L is calculated as:

$$141 \quad F_L = \frac{C_L}{2} \rho u^2 A \quad (4)$$

142 where A is the plan view cross-sectional area of the grain and C_L is an empirical lift
 143 coefficient assumed to be 0.2 (Wiberg and Smith, 1985). The boundary shear stress at
 144 the threshold of motion, τ_c , is calculated by rearranging the preceding equations (for
 145 the full derivation see Kirchner *et al.*, 1990):

$$146 \quad \tau_c = \frac{C_D}{2} \rho u^2 W(z) + \frac{C_L}{2} \rho u^2 A \quad (5)$$

147 where:

$$148 \quad W(z) = \frac{D}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right) \quad z > z_0$$

$$W(z) = 0 \quad z < z_0 \quad (6)$$

149 Kirchner *et al.*'s [1990] equation is multiplied by 0.1 so that inputs in S.I. units
 150 produce a value of τ_c in Pa. Equation 5 assumes that grains have a circular cross-
 151 section. A dimensionless value of τ_c , (τ_c^*) is calculated as:

152
$$\tau_{\varepsilon}^* = \frac{\varepsilon}{(R-AB)^i} \quad (7).$$

153 **2.2. Field site and field methods**

154 Field data were collected from Bury Green Brook, Hertfordshire (51° 50' N, 0° 4' E),
 155 a small stream with a well-defined riffle-pool morphology (Figure 1). The study reach
 156 varies in bankfull channel width from 2.8 to 6.5 m. The mean bed slope over the ~80
 157 m reach is 0.008 and the mean flow depth (variable over pools and riffles) at bankfull
 158 discharge is 1.3 m. Bury Green Brook drains a rural catchment of 21.8 km², underlain
 159 by Upper Chalk which is extensively overlain by boulder clay and glacial sands, with
 160 gravel and alluvium in the valley floor. This combination results in a flashy
 161 hydrograph and sustained flows over the autumn-spring flood season, with a dry bed
 162 during the summer months. These conditions create bed mobilising events in most
 163 years, followed by periods when the dry water-worked river bed can be accessed
 164 enabling Terrestrial Laser Scanning and other field data to be collected. No flow
 165 gauging exists for the stream hence flow data are unavailable for the site. Data
 166 including TLS were collected from ~ 1 m² patches of the river bed in both September
 167 2006 and June/July 2009. For the flow modelling, an 80 m reach was surveyed using
 168 TLS in 2009. The reach included five pool-riffle sequences.

169 **2.3. Patch-scale field data**

170 Patch scale data were collected in both years. These data provide values of D , Φ , m , p
 171 and e for grains in the different facies, which are used to parameterise the modified
 172 model of Kirchner *et al.* (1990). The data also provide supplementary evidence on
 173 sediment structure. Representative patches were selected from the different facies
 174 present in the channel: pools, riffles, pool exits and pool heads. These facies were

175 visually identified and the local flow direction was estimated from the channel
176 topography and the alignment of wake deposits (sensu Reid *et al.*, 1992). Subsequent
177 analysis of the channel long-profile and hydraulics confirmed the field identification.

178

179 The analysed patches comprised two pools, two pool exits and two riffles in 2006 and
180 four pools, three pool exits, three riffles and one pool head in 2009. Analysis
181 primarily focuses on the 2009 patches. From each patch, the following measurements
182 were taken: 1) Terrestrial Laser Scanner (TLS) data to record the grain-scale patch
183 topography; 2) pivoting angle measurements from individual grains, 3) lift force
184 measurements from individual grains; 4) bulk grain size distribution.

185 *TLS data*

186 TLS data were collected from each patch following the method of Hodge *et al.*
187 (2009a). Data were collected from two opposing scanner positions, at a point spacing
188 of 2 mm (for comparison, the finest median grain size is 18 mm). Three repeat scans
189 were collected from each scanner position. The multiple scans were averaged and
190 filtered following Hodge *et al.* (2009a), and Digital Terrain Models (DTM) were
191 interpolated from the point data at 1 mm spacing. DTMs were detrended in order to
192 remove the influence of reach-scale topography; detrending was achieved by fitting a
193 second order polynomial surface to the DTM, and then subtracting this surface from
194 the DTM. The mean patch elevation was subtracted from the DTM to produce a mean
195 elevation of 0 m. The patch bed slope (β) was determined by initially calculating the
196 slope between all pairs of elevations 10 cm apart in the downstream direction, and
197 then taking the mean of all these slopes. Analysis of the DTMs can also provide
198 information on sediment structure. Given the relatively small size of the grains
199 compared with the resolution of TLS data, such analysis is here limited to

200 distributions of surface elevations (Hodge *et al.*, 2009b) and the exposure of
201 individual grains.

202 *Pivoting angle measurements*

203 Pivoting angles are a function of the horizontal force required to entrain a grain and
204 therefore are a measure of grain geometry and packing. Following Johnston *et al.*,
205 (1998) pivoting angle (Φ) is estimated using:

$$206 \quad \tan(\Phi) = \frac{F_d - F_w \sin(\beta)}{F_w \cos(\beta)} \quad (8)$$

207 where F_d is the maximum horizontal force required to dislodge the grain. Force was
208 applied using the probe of a force gauge, with the gauge recording the maximum
209 force. F_w is the weight of the grain and the bed slope, β , is positive if bed elevation
210 increases downstream. Accounting for the effect of β is important when $|\beta|$ is $> 2^\circ$ and
211 Φ is $< 70^\circ$. In 2006, pivoting angles were measured for 39 or 40 grains per patch, and
212 in 2009 for 50 grains per patch.

213 *Lift force measurements*

214 For unconstrained grains, the lift force (F_L) required to vertically entrain a grain is
215 equal to the grain weight (F_w). To quantify the extra force required to overcome any
216 additional impediments to grain entrainment, such as grain packing and mortaring, F_L
217 is expressed as a multiple of F_w , which is termed m : $m = F_L/F_w$. Lift forces were
218 measured for between 14 and 25 grains in each of the 2009 patches (with the
219 exception of patch P4). Grains were selected using a grid. A 20 cm length of nylon
220 string was stuck to the middle of the exposed area of each grain using a bead of
221 superglue without disturbing the grain. A force gauge was then used to measure the

222 maximum force required to vertically entrain the grain. For each grain, grain weight
223 and axes dimensions were also recorded.

224 *Bulk grain size distribution*

225 Samples for bulk grain size analysis were collected from the 2009 and 2006 patches
226 by skimming the surface layer from an undisturbed area of the patch. The sediment
227 samples were dry sieved through half-phi sieves and weighed.

228 *Grain exposure*

229 Grain exposure was measured for individual grains in the DTMs. Grains were selected
230 using a grid, and manually digitised with cross-reference to photographs of the
231 patches. Only grains with a long axis of > 20 mm were digitised; smaller grains were
232 harder to identify unambiguously. If no grain could be identified at the grid
233 intersection, then a nearby grain was digitised. Between 20 and 45 grains were
234 digitised from each 2009 patch, with the exception of patch E3 where the DTM
235 quality was too poor. In the Kirchner *et al.* (1990) model, grain exposure is
236 represented through 1D measures: grain exposure (e) and grain projection (p , Figure
237 2c). Two further measures that better take into account the 2.5D nature of the TLS
238 data are also included for comparison; these are profiles of exposed width of the grain
239 (which describes direct sheltering) and of the extent of sheltering from upstream
240 grains (Figure 2).

241

242 Grain projection, p , is the difference between the maximum height of the grain and
243 the local mean bed elevation (Kirchner *et al.*, 1990). The local bed is the area of the
244 bed that extends a distance equal to D_{84} upstream and downstream of the grain. D_{84}
245 is calculated from the GSD measured from the grains used in pivoting angle and lift

246 analysis. e is defined as the difference between the maximum height of the grain and
247 the maximum upstream elevation; maximum upstream elevation is measured in the
248 area that extends a distance equal to D_{84} upstream of the grain. If the maximum
249 upstream elevation and the maximum grain height occur at different positions across
250 the face of the grain, then this definition underestimates grain exposure. To
251 incorporate the cross-stream profile of the grain, e was calculated for mm-wide, flow-
252 parallel strips across the cross stream profile, with the maximum grain height and
253 elevation being those measured within that strip. If the grain elevation was less than
254 the maximum elevation, $e = 0$. The value of e for the grain is the mean of e for all
255 strips.

256

257 Grain exposure is produced by two components: direct and remote sheltering
258 (McEwan *et al.*, 2004). Direct sheltering is the effect of contacting upstream grains
259 reducing the effective area of the grain in question. Remote sheltering is caused by the
260 wake of upstream grains reducing the fluid drag force that is applied to the grain
261 (Schmeeckle and Nelson, 2003; Heald *et al.*, 2004). Fluid drag is most reduced
262 immediately behind an obstacle, with an approximately linear return to unobstructed
263 flow over a maximum sheltering distance of eight to ten grain diameters (Schmeeckle
264 and Nelson, 2003; Heald *et al.*, 2004). p and e are calculated over a single grain
265 length, therefore primarily reflect direct sheltering.

266

267 To produce profiles that demonstrate the effects of both direct and remote sheltering
268 over the elevation of a grain, the exposed face of each digitised grain is divided into
269 cells 1 mm wide by 0.2 mm high. At each elevation, the width of the exposed face (W ,
270 in mm) is equal to the number of cells. Plotting W against height (h) (Figure 2d)

271 profiles the shape and height of the exposed grain face and hence the area of the grain
272 that is not affected by direct sheltering. For comparison between grains, W and h are
273 normalised by grain diameter D .

274

275 To quantify the effect of remote sheltering, a weighting (s) is calculated for each cell
276 as:

$$277 \quad \begin{aligned} s &= d_u / d_t & d_u \leq d_t \\ s &= 1 & d_u > d_t \end{aligned} \quad (9)$$

278 where d_u is the distance of the first upstream grain sheltering that cell, and d_t is the
279 maximum sheltering distance; d_t is taken to be 200 mm, which is broadly consistent
280 with sheltering occurring over eight to ten grain diameters. Figures 2a and b show an
281 example of the distribution of s over the exposed face of a grain. s is inversely
282 proportional to the reduction in flow strength and hence the degree of remote
283 sheltering. Profiles of mean s against h/D show the vertical variation in s (Figure 2e),
284 indicating how remote sheltering varies down the grain face.

285 **2.4. 2D flow modelling**

286 The field data and grain entrainment model will demonstrate the effect of sediment
287 structure on τ_c in different facies. However, whether or not a grain is entrained also
288 depends on the magnitude of the bed shear stress (τ) applied to that grain. Shear stress
289 in riffle-pool sequences is spatially variable (Booker *et al.* 2001; McWilliams *et al.*,
290 2006), and therefore it is instructive to compare the magnitude of spatial variation in
291 applied τ with the magnitude of variation in τ_c . We do not have flow data from the
292 ungauged Bury Green Brook, and so cannot directly calculate τ . Instead we use a 2D
293 flow model to reconstruct a bankfull event and to estimate the magnitude and spatial
294 distribution of τ .

295

296 Flow processes in riffle-pool sequences are strongly 2D and potentially 3D (Booker *et*
297 *al.* 2001; McWilliams *et al.*, 2006). Although this may suggest the use of a 3D flow
298 model, 3D flow models require spatially distributed 3D velocity data for calibration
299 and verification (Lane *et al.*, 1999), which are not available for this ephemeral river.
300 Use of a 2D model provides a balance between model capability and complexity (Cao
301 *et al.*, 2003), and so we estimate τ using the depth-averaged 2D flow model Hydro2de
302 (Beffa and Connell, 2001). Hydro2de solves the Navier-Stokes depth-averaged
303 shallow water flow equations in conservation form, in which depth and specific flow
304 are related to spatial coordinates [x, y] using conservation of volume and momentum.
305 Bed shear stresses are calculated using the Manning's friction law (Beffa and Connell,
306 2001). Hydro2de can reproduce spatial variations in bed topography and roughness,
307 which are a key feature of riffle-pool sequences. Using a 2D model to calculate bed τ
308 in a riffle-pool sequences is supported by the work of Pasternack *et al.* (2006) and
309 Cao *et al.* (2003).

310

311 Our validation data is limited to a series of trash line elevations that correspond to a
312 bankfull event. These trash lines were mapped with a total station, and provide an
313 estimate of water depth and water surface slope. As our flow modelling is therefore
314 relatively poorly constrained, we identify the effect that both discharge and roughness
315 parameterisation have on the distribution of τ , and propagate this analysis through to
316 the comparison with the entrainment model results. We also consider the extent to
317 which our conclusions are sensitive to the exact values of the flow model results.

318

319 To construct a reach scale DEM for input to Hydro2de, TLS was used to measure the
320 topography of the channel and banks at a mean point spacing of 0.01 m. The TLS data
321 were subsequently processed through a combination of manual point cloud editing
322 and automated minimum elevation filtering to remove extraneous data. The latter
323 process involves gridding the data at a coarser resolution of 0.1 m, and then retaining
324 the minimum elevation within each cell, thereby increasing the likelihood that the
325 chosen point is representative of the bare earth model. The output DEM, with a grid
326 spacing of 0.1 m, was used for the flow modelling.

327

328 Hydro2de can operate using spatial distributions of roughness, defined in the model
329 using dimensionless Manning's n values. Manning's n was calculated using the
330 formula devised by Ferguson (2007):

$$331 \quad (8/f)^{1/2} = a_1 a_2 (R/D_{84}) / [a_1 + a_2 (R/D_{84})^{5/3}]^{1/2}, \quad n = R^{1/6} (f/8g)^{1/2}, \quad (10)$$

332 where f is the Darcy-Weisbach friction factor and R is the hydraulic radius, and with
333 $a_1 = 6.5$ and $a_2 = 2.5$ as suggested by Ferguson (2007; 2010). Ferguson (2007)'s
334 formula is an improvement over the commonly used Strickler formulation because the
335 former accounts for the effect of relative submergence on Manning's n . We note
336 however that under bankfull conditions in Bury Green Brook, R/D_{84} varies between ~
337 7 (riffles) and ~ 14 (pools), and thus values of Manning's n calculated using equation
338 10 and the Strickler formulation are not greatly different.

339

340 Values of Manning's n were calculated for all patches with grain size data. R was
341 calculated for each patch under the flow conditions described by the trash marks. The
342 trash data were interpolated to produce a best fit water surface for this flow event, and
343 the elevation of this surface was used to calculate R at each patch location. Hydro2de

344 was parameterised using an average value of Manning's n from the riffle patches for
345 all riffle areas ($n = 0.034$), whereas individual values of Manning's n were used for
346 the pools ($n = 0.03$ to 0.031). This is because the pools were spatially isolated,
347 whereas it was not always possible to identify clear boundaries between the different
348 riffles. The roughness of the banks was set at $n = 0.1$ according to values derived from
349 a stream with comparable bed and bank morphology and roughness (Booker *et al.*,
350 2001).

351

352 The flow model was run at seven different discharges between 2.2 and $2.8 \text{ m}^3\text{s}^{-1}$; the
353 discharge that best replicated the bankfull conditions was identified by calculating the
354 RMSE between the modelled water surface and the water surface interpolated from
355 the trashlines. This range of discharges is comparable to bankfull flows recorded for
356 an adjacent similar sized stream (Stansted Brook; gauge number 38028, drainage area:
357 25.9 km^2).

358

359 Identifying an appropriate value of Manning's n is a known source of uncertainty in
360 flow models, and we note that we are applying a relationship derived from 1D data to
361 a 2D model. We therefore also used a high and a low parameterisation of Manning's n
362 to quantify the effect on τ . Ferguson (2010) compiled measured values of Manning's n
363 from > 400 rivers. We used the spread of these data (in Figure 2B in Ferguson, 2010)
364 to identify plausible upper and lower values of Manning's n at values of R/D_{84} that are
365 relevant to the riffles and pools in Bury Green Brook. The low Manning's n
366 parameterisation is $n = 0.017$ and $n = 0.014$ for riffles and pools respectively, and the
367 high parameterisation is $n = 0.097$ and $n = 0.051$. Both parameterisations were run at
368 the same range of discharges as the standard parameterisation. For the higher

369 Manning's n parameterisation these discharges flooded the model domain, and so a
370 range of lower discharges between 1.4 and $1.8 \text{ m}^3\text{s}^{-1}$ were also run.

371 **3. Field results**

372 Results are presented from the grain-scale field measurements and CFD modelling.
373 The field data are then used to parameterise the grain entrainment model. This section
374 analyses the grain-scale properties to identify how they vary both within and between
375 facies, and whether they vary as a function of grain size.

376 **3.1. Grain size data**

377 Grain size distributions (Figure 3) were calculated from both a bulk surface sample
378 (2009 patches) and the grid-based samples of grains used for the pivoting and lift
379 analyses (2006 and 2009 patches). The former describes the GSD by weight of the
380 entire armour layer, whereas the latter gives the GSD by area of the surface grains,
381 and therefore is more representative in terms of the grains that will contribute to
382 bedload transport. GSD percentiles used in subsequent analyses are calculated from
383 the grid-based samples.

384

385 Although most patches have similar GSDs, riffle patches tend to be coarser, whereas
386 pool and pool exit patches tend to be finer. For the 2009 grid-based GSDs, pool
387 patches have D_{50} between 27 and 38 mm, pool-exit patches have D_{50} between 28 and
388 37 mm and riffle patches have D_{50} between 35 and 42 mm. This pattern of finer pools
389 and pool-exits and coarser riffles is also found in the 2006 data. 2006 patches tend to
390 be finer than 2009 patches of the same facies; 2006 pools have D_{50} between 18 and 26
391 mm, 2006 pool exits have D_{50} between 18 and 30mm and 2006 riffles have D_{50}
392 between 24 and 33 mm. Grain sphericity does not vary significantly between the

393 different facies (ANOVA, $p = 0.31$), with a mean value of ~ 0.7 . Grain form ($a-b/a-c$,
394 where a , b and c are axes lengths) does vary significantly between the facies
395 (ANOVA, $p = 0.002$); however, the difference in mean value between facies is small
396 (mean form values for pool, pool exit and riffle facies are 0.56, 0.55 and 0.48).

397 **3.2. Pivoting angles**

398 Distributions of pivoting angles (Φ) from both 2006 and 2009 (Figure 4a and b) show
399 that pools tend to have lower values and a larger range of Φ , whereas pool exits tend
400 to have higher values of Φ and a narrower range. Riffles typically fall somewhere
401 between these two extremes. The main difference between the 2006 and 2009 data is
402 that the 2006 values of Φ for a given facies are generally higher than those from 2009.

403

404 For both the 2006 and the 2009 data, analysis of covariance of Φ as a function of both
405 facies and relative grain size (D/D_{50}) indicates that both facies and D/D_{50} have a
406 significant influence on pivoting angle (respective p-values of < 0.0001 and < 0.0001
407 for 2006 and < 0.0001 and 0.02 for 2009). Differences between facies are further
408 identified by fitting linear regressions to Φ as a function of D/D_{50} for all data from
409 each of the facies. For the 2009 data, this analysis reveals a significant difference
410 between the regression slopes of the pool and pool exit facies (significant at $\alpha = 0.05$)
411 but no significant difference in regression intercepts. Regression lines fitted to the
412 different 2006 facies are not significantly different. Using the same analysis to
413 investigate similarities between patches within a facies from the same year reveals no
414 significant difference in regression slopes, and a significant difference in intercepts
415 only between 2009 patches E1 and E3. This indicates that there is greater variability
416 between facies than within patches from a particular facies.

417

418 Values of Φ display a large amount of scatter for a given value of D/D_{50} , as has been
 419 identified in previous investigations (Kirchner *et al.*, 1990; Johnston *et al.*, 1998).
 420 Percentiles of Φ calculated for binned values of D/D_{50} (Figure 4) show that in the
 421 2009 pool facies, percentiles of Φ are approximately evenly distributed for a given
 422 value of D/D_{50} , whereas in the 2009 riffle and pool exit facies, the upper 60 % of the
 423 values of Φ fall between 80 and 90°. The 2006 data show a similar pattern, but with
 424 higher values of Φ .

425

426 Pivoting angles have previously been measured for *in-situ* grains in the field by
 427 Johnston *et al.* (1998). Values of Φ measured in Bury Green Brook are generally
 428 higher than those measured by Johnston *et al.* (1998); fits of the form:

429
$$\Phi = 62 + 21(D/D_{50})^{\epsilon} \quad (11)$$

430 to the Bury Green Brook data predict that a grain of size $D/D_{50} = 1$ will have a mean
 431 Φ of 62° in the pool facies, 83° in the pool exits and 76° in the riffles. In contrast, for
 432 the same relative sized grain, Johnston *et al.* (1998) predict mean Φ of between 49
 433 and 62°. The field sites of Johnston *et al.* (1998) have similar D_{50} to the Bury Green
 434 Brook patches. The difference between the two sets of results could be because
 435 Johnston *et al.* (1998) selected field patches that lacked spatial sorting and clustering
 436 and had little sand or silt among the gravel, thereby choosing patches more similar to
 437 the Bury Green Brook pools. An alternative explanation could be sampling strategy;
 438 Johnston *et al.* (1998) randomly sampled available particles (i.e. those that could
 439 move without first moving other grains), whereas the grid-based sampling applied in
 440 Bury Green Brook meant that pivoting angles were measured regardless of grain
 441 availability.

442 **3.3. Lift forces**

443 Lift force measurements (m) also vary between the facies (Figure 5). Generally, grains
444 in pools have lower values of m (mean m for all pool measurements is 1.5), whereas
445 grains in pool exits have higher values (mean m for all pool exit measurements is 2.7).
446 Lift forces are not a significant function of relative grain size (Figure 5); linear
447 regression of m against D/D_{50} for all data from a given facies does not show a
448 significant relationship for either the pool or riffle facies (at $\alpha = 0.05$). For the pool
449 exit facies, $p = 0.01$; removing the outlying point at $D/D_{50} = 2.4$ increases p to 0.02.
450 Mean values of m are not significantly different between patches from the same facies
451 (ANOVA, $p > 0.09$). Mean values of m are, however, significantly different between
452 the different facies (ANOVA, $p < 0.0001$). Furthermore, the mean value of m in the
453 pool exit patches is significantly greater than in the other three facies.

454

455 In the field, the high values of m for grains in the pool exit patches were identified as
456 being the result of mortaring, i.e. the presence of a layer of cohesive fine-grained
457 sediment that cements grains together. Of the lift measurements, mortaring was
458 identified as affecting 53 % of the pool exit grains, 18 % of the riffle grains and 17 %
459 of the pool grains. Furthermore, the pool exit grains with mortaring had a mean m
460 value of 3.9, whereas for grains without mortaring, mean m was 1.4. The presence of
461 mortaring is not apparent in the bulk GSDs though; although patch E2 has a high
462 proportion of fine sediment, neither patch E1 nor E3 has elevated levels of fine
463 sediment (Figure 3a).

464 **3.4. Grain exposure**

465 *Grain protrusion and exposure*

466 Grain protrusion (p) and exposure (e) provide a 1D measure of grain exposure (Figure
467 2). Both p and e are normalised by D . p/D shows no significant relationship with
468 D/D_{50} (Figure 6a); regression lines all have a p-value of at least 0.08 and the slopes
469 are not significantly different to zero. Distributions of p/D are significantly different
470 between facies (ANOVA, $p = 0.0001$), with the mean value of p/D for grains from
471 pool patches being significantly higher than the mean for grains from either pool exit
472 or riffle patches.

473

474 Distributions of p/D for all grains from a facies are not significantly different to a
475 normal distribution; depending on the facies the mean varies between 0.37 and 0.47
476 and the standard deviation between 0.16 and 0.21. Grain exposure (e/D) shows a
477 strong linear relationship with p/D (Figure 6b); linear regressions of e/D against p/D
478 for each facies having a regression p-value of < 0.0001 . Residuals from this
479 relationship are described by a normal distribution.

480 *Direct and remote sheltering*

481 Grain exposure is a function of both the area of the grain projecting above the
482 boundary between the grain and upstream neighbouring grains, and the extent of
483 sheltering applied by upstream grains (Figure 2). Both components vary with
484 elevation from the top to the bottom of the grain. Figure 7a shows how the median
485 width of the exposed grain area (W) varies with height below the top of the grain (h).
486 Both h and W are normalised by D , and W/D for a completely exposed sphere is added
487 for comparison. Data from each facies displayed considerable variation between the

488 profiles of individual grains because of the variable grain shapes and geometry of
489 sheltering grains. Consequently, the 95 % error bands around the median value of
490 W/D are relatively wide. Within each facies, there was no systematic difference
491 between profiles of W/D for different sized grains, down to the size of the smallest
492 identified grains (20 mm).

493

494 For all facies, in the upper part of the profile from $h/D = 1$ to h/D between 0.8 and 0.9,
495 median W/D is approximated by the profile of a sphere. Below this, W/D is less than
496 the value of W/D for a fully exposed sphere. By $h/D = 0.5$, all profiles of median W/D
497 drop to $W/D < 0.2$. This result is consistent with grains being embedded in the surface
498 by about half their diameter. Between $h/D = 0.5$ and 0.8, the grains in pool patches
499 have the highest median value of W/D . Pool exit grains display the smallest values.
500 This difference between pool and pool exit grains can be attributed to differences in
501 grain packing between the different facies. An alternative explanation of differences
502 in grain shape can be ruled out because there is no significant difference between the
503 different facies in the ratio of the $a:b$ axes of the grains for which exposure was
504 calculated (ANOVA, $p = 0.34$).

505

506 Profiles of the median sheltering weighting (s), i.e. the median distance of upstream
507 sheltering grains, also show a difference between the facies (Figure 7b). In each
508 facies, as h/D decreases, s decreases, i.e. grains become more sheltered. For any given
509 value of h/D , the profile from pool grains has the highest value of s , indicating the
510 least sheltering, whereas riffle grains are the most sheltered; this variation indicates a
511 difference in sediment packing between these facies.

512 **3.5. Surface elevations**

513 Grain exposure measurements indicate that grains in pool patches are relatively more
514 exposed than grains in other facies, suggesting a difference in grain packing. This
515 difference can also be seen in the distributions of surface elevations in the DTMs
516 (Figure 8). The DTMs have been detrended, therefore the distribution of elevations
517 reflects the geometry of the patch at the grain-scale. A large range of elevations
518 suggests that grains are loosely packed, whereas a narrower range indicates tighter
519 packing. When elevations are normalised by D_{50} , pool patches generally have a higher
520 range of elevations than other patches, with the range between the 5th and 95th
521 elevation percentiles being between 0.99 and $2.01D_{50}$. Riffles consistently have a
522 narrower range of elevations, with the range from the 5th to the 95th percentiles being
523 from 0.73 to $1.10 D_{50}$. The 2009 pool exit patches also have a narrow range of
524 elevations, whereas the 2006 pool exit patches have a much larger range.

525 **3.6. Field results summary**

526 Field measurements and analysis of DTMs from different facies within Bury Green
527 Brook have identified significant differences between the facies in terms of the grain-
528 scale properties. These differences in turn will influence the critical shear stress at
529 which grains from the different facies are entrained. Furthermore, the data also help
530 to identify the aspects of sediment geometry that are causing these differences.

531

532 The field data show that grains in the pool patches, in comparison with the other
533 patches, have relatively lower pivoting angles and relatively higher grain exposure,
534 both in terms of total exposed area and the location of upstream sheltering grains. Lift
535 force measurements are typically only one or two multiples of grain weight, and grain
536 sizes are relatively smaller. All of these variables suggest that grains in pool patches

537 are likely to be more easily entrained than grains in either riffle or pool exit patches.
538 Riffle and pool exit patches have similar grain-scale properties to each other, with the
539 exception that grains in pool exit patches recorded higher lift forces. Grains in the
540 pool head patch appear to have properties intermediate to the other facies, but this is
541 limited by the single patch sample size.

542

543 The field data also suggest a possible cause of the differences in properties relating to
544 grain entrainment. The higher grain exposure and surface roughness in the pool
545 patches indicates that the grains are more loosely packed. Looser packing means that
546 grains sit in shallower pockets, resulting in the lower pivoting angles. Lower exposure
547 and roughness in the pool exit and riffle patches suggest tighter sediment packing.

548

549 The field data also describe differences between the patches in 2006 and in 2009. The
550 relative variation in D_{50} between different facies is the same in both years, i.e. pool
551 patches are relatively finer and riffle patches are relatively coarser. However, within a
552 facies the 2006 patches are consistently finer than the 2009 patches. The same is also
553 true of pivoting angle measurements. In both years pivoting angles are lowest in the
554 pool patches; however pivoting angles measured from the 2006 patches are higher
555 than those measured in 2009. The reasons for these temporal variations are unknown;
556 differences in measurement technique are unlikely because pivoting angles were
557 measured by the same person on both occasions. A plausible explanation is the
558 magnitude and history of recent flood events. After a large transport event grains may
559 be deposited with a range of pivoting angles, whereas subsequent smaller events may
560 preferentially reposition grains with lower pivoting angles, increasing the average
561 pivoting angle. Changes in sediment GSD could be a function of the connectivity to

562 upstream sediment supplies (Hooke, 2003). The finer GSD in 2006 could also be
563 associated with a higher degree of mortaring, which would also increase pivoting
564 angles.

565 **4. Flow modelling results**

566 The flow modelling results show that the water surface elevation interpolated from the
567 trash data can be reproduced with both the low and the standard parameterisations of
568 Manning's n (Figure 9). There are still discrepancies at around 20 m and 38 m
569 downstream, although these trash markers could potentially relate to a different high
570 flow event. Note that at high parameterisations of n , the range of discharges (2.2 – 2.8
571 m^3s^{-1}) used for the aforementioned scenarios all flooded the model domain resulting
572 in very high water surfaces relative to the trash markers. A range of lower discharges
573 (1.4 – 1.8 m^3s^{-1}) were also modelled in an attempt to replicate the water surface slope
574 as per the low and standard parameterisations of Manning's n . The lowest RMSEs are
575 given by a discharge of 2.6 m^3s^{-1} (low n , RMSE = 0.024) and of 2.5 m^3s^{-1} (standard n ,
576 RMSE = 0.027). At high n , the lowest RMSE is given by a discharge of 1.5 m^3s^{-1}
577 (RMSE = 0.051). This RMSE is almost twice that given by the other two
578 parameterisations, and therefore the high n model results are not further considered.

579

580 All model runs show strong spatial variation in the distribution of both depth-
581 averaged flow velocity and bed shear stress (τ) within the channel, with highest values
582 typically occurring over riffles (Figure 10). For each sequence of pool, pool exit and
583 riffle patches, τ is lowest in the pool exit, followed by the pool, with highest τ in the
584 riffle (Figure 11). Under the optimum (lowest RMSE) standard Manning's n
585 parameterisation, median τ in the riffle patches was between 11 and 22 Pa, whereas
586 median τ in the pool patches was between 4 and 17 Pa. Across all seven different

587 discharges the total range of median τ is between 4 and 18 Pa in pools, and 10 and 23
588 Pa in riffles. Values of τ are lower under the optimum low Manning's n
589 parameterisation, with median riffle τ between 2 and 6 Pa, and median pool τ between
590 1 and 4 Pa; these ranges are the same as the total range across all seven discharges.
591 These results indicate that, under bankfull conditions, maintenance of the pool-riffle
592 sequences in the study reach appears not to be the result of a velocity or shear stress
593 reversal.

594

595 The validity of the modelled shear stress estimates is difficult to assess further due to
596 the lack of suitable validation flow data. Furthermore, an alternative method for
597 calculating shear stress, the reach averaged depth-slope product, is not comparable
598 because of its assumption of uniform flow (flow through riffle-pool sequences is
599 typically non-uniform, Figure 2) and the fact that it tends to overestimate the effective
600 shear acting on a grain (Robert, 1990). Taking these uncertainties into account, we
601 carry forward both the low and standard Manning's n parameterisations to a
602 comparison with the entrainment model results.

603 **5. Grain entrainment model**

604 **5.1. Model results**

605 The field data are used to derive the parameters for the grain entrainment model of
606 Kirchner *et al.* (1990). Using a Monte-Carlo approach and equation 5, values of
607 critical entrainment shear stress (τ_c) are calculated for a large number (4800) of
608 simulated grains from each of the pool, pool exit and riffle facies. The properties of
609 each of these grains are determined as outlined in Table 1. Pivoting angle is calculated
610 as a function of relative grain size, whereas other properties were not found to be size
611 dependent. Grain exposure is parameterised using p and e , which only includes the

612 sheltering effects of grains up to a distance of D_{84} upstream. In order to calculate
613 exposed grain area, grains are assumed to be spherical. This assumption does not
614 greatly affect the calculations. In terms of F_w , the ratios of a/b and c/b for an average
615 grain are such that $a/b \times c/b \approx 1$, therefore the volume of a grain is well approximated
616 by the volume of a sphere with diameter b . In terms of F_D , the potential exposed grain
617 area is assumed to be a circle with diameter b . Use of an ellipse with width b and
618 height c only increases predicted widths by up to 20 %. Such discrepancy is small
619 compared to the differences between idealised and actual exposure profiles shown in
620 Figure 7.

621

622 In the field, different parameter values were measured from different grains, therefore
623 possible relationships between parameters (e.g. pivoting angle and exposure) cannot
624 be quantified from the field data. Such parameter values, however, are not likely to be
625 completely independent of one another, as shown in the theoretical relationships
626 derived by Kirchner *et al.* (1990). For example, a grain in a shallow pocket in the bed
627 will have both a low pivoting angle and a high exposure. Furthermore, values of Φ
628 and m measured in the field are likely to be related, as they will both capture the effect
629 of properties such as mortaring; for example patches E1 and E2 have high values of
630 both variables.

631

632 In order to investigate the effect of these possible inter-relations, the grain entrainment
633 model is run in two forms, A and B. In model A, Φ and p for a single grain are
634 assumed to be independent of each other, and field measurements of Φ are assumed to
635 incorporate the effect of mortaring and therefore the value of m for all grains is 1. In
636 model B, for each grain, Φ is inversely proportional to p . If the percentile randomly

637 selected to interpolate a value of Φ is n , then the selected value of p is that of the 100
638 – n^{th} percentile of the relevant normal distribution. The effect of mortaring on lift
639 forces is incorporated by selecting values of m from the field data distributions. Model
640 A is more strictly derived from the field data, and, by setting $m = 1$, does not allow the
641 effect of mortaring to be potentially double counted; it therefore is a more
642 conservative model. Model B is more speculative; the proposed relationship between
643 Φ and p is consistent with Kirchner *et al.* (1990), but cannot be tested with the field
644 data. Furthermore, both Φ and m may include the effect of mortar. Model B estimates
645 the additional influence of these factors.

646

647 Distributions of τ_c calculated for the three different facies and from the two model
648 variants are shown in Figure 12a. Using model A, grains in the pool facies have the
649 lowest values of τ_c , with a median of 37.7 Pa. Grains in pool exit and riffle facies have
650 increasing values of τ_c , with respective medians of 52.6 and 65.4 Pa. The mean values
651 of τ_c from the different facies are significantly different to each other (ANOVA of
652 $\log(\tau_c)$, $p < 0.0001$).

653

654 Using model B, grains from the pool again have the lowest values of τ_c . The median
655 value of τ_c of 36.2 Pa is similar to that in model A, but 17 %, rather than the previous
656 7 %, of grains have values of $\tau_c < 20$ Pa. Model B produces distributions of τ_c for pool
657 exit and riffle grains that are more similar to each other, although the median values
658 of τ_c are reversed; median τ_c is 77.4 Pa and 68.1 Pa for the pool exit and riffle grains
659 respectively. This similarity between the two distributions is mainly because of an
660 increase in the value of τ_c for pool exit grains. Both distributions have a longer tail of

661 lower values in model B than in model A. Mean values of $\log(\tau_c)$ for all three facies
662 are again significantly different from each other.

663

664 The longer low value tails in model B results are because of the inverse relationship
665 between Φ and p ; a low value of Φ is automatically coupled with a high value of p ,
666 both of which produce a lower value of τ_c . Such pairings will be less common in
667 model A, and therefore there are fewer grains with low values of τ_c . The higher values
668 of τ_c for pool exit grains in model B is the effect of incorporating field measurements
669 of m , which were highest in pool exit facies.

670

671 To isolate the effects of grain size and sediment structure, models A and B were also
672 run using the pool exit and riffle GSDs, but with pivoting angle and exposure
673 parameterised from the pool field data. The resulting median values of τ_c were 38.5
674 and 47.2 Pa for the pool exit and riffle GSDs respectively for model A and 36.8 and
675 44.2 Pa for model B. The effect of the observed tightly packed sediment structure
676 (expressed through p , e and Φ) in the pool exit and riffle facies is therefore to increase
677 median τ_c by between 37 and 39 % in model A and between 54 and 110 % in model
678 B. The larger increase in model B is because of the higher values of m .

679

680 The relationship between D/D_{50} and τ_c^* (Figure 12b) predicted by the grain
681 entrainment model shows that τ_c^* is inversely proportional to D/D_{50} , with linear
682 regressions of $\log(\tau_c^*)$ against $\log(D/D_{50})$ having a gradient of ~ -1 . This is
683 consistent with the results of other studies presented by Johnston *et al.* (1998). This
684 relationship shows that within a facies τ_c is approximately invariant with grain size,

685 and therefore grain entrainment is also controlled by factors including sediment
686 structure.

687 **5.2. Comparison with flow modelling**

688 Comparison between the distributions of τ_c predicted using the modified Kirchner *et*
689 *al.* (1990) model (Figure 12) and the distributions of τ predicted from the CFD model
690 (Figure 11) allow initial estimates of the stability of sediment in different units of the
691 channel to be assessed. The flow modelling produced two alternative
692 parameterisations that could not be distinguished between on the basis of the trash
693 elevation data, and therefore we present results from both low and standard
694 Manning's n parameterisations. For this assessment, shear stress data from different
695 patches within the same facies are combined, and are compared with entrainment
696 model results using both models A and B.

697

698 In each of the four different comparisons (low and standard Manning's n, entrainment
699 models A and B), grains in pools are the most likely to be entrained (Figure 13).
700 Under the standard Manning's n parameterisation and optimum discharge, results
701 from models A and B respectively give an average entrainment of 1.8 % and 5.6 % in
702 pools, with 12 % and 22 % entrainment under the highest values of τ . In contrast,
703 entrainment in riffles reaches a maximum of 5.9 % under both models. Grains in pool
704 exits are the most stable, with a maximum of 1.9 % entrainment. Comparisons using
705 flow model runs with different values of discharge give very similar results (Figure
706 13a). Using the data from the low Manning's n parameterisation and optimum
707 discharge produces the same pattern of results, but with lower proportions of
708 entrainment (Figure 13b). Maximum entrainment from pools is 0.6 and 3.5 % for
709 entrainment models A and B respectively, whereas entrainment from riffles is a

710 maximum of 0.3 % and from pool exits is a maximum of 0.01%. Again, flow data
711 from different discharges produces comparable results (Figure 13b).

712

713 From consideration solely of the predicted shear stress (Figure 11), sediment would
714 be expected to be most mobile under the highest shear stresses experienced by riffles.

715 Comparison between the flow and entrainment model results suggests that the effect

716 of sediment structure on τ_c is such that it reverses the pattern of sediment mobility to

717 one where under bankfull flow, sediment in pools is most mobile. In Bury Green

718 Brook, sediment structure alone appears to be sufficient to maintain the riffle-pool

719 topography.

720

721 This conclusion holds across both the low and standard Manning's n flow model

722 parameterisations and across a range of discharges within each. Furthermore, the

723 general conclusion that under high flow grains are more mobile in pools than in riffles

724 also holds under a range of alternative flow model results. If the shear stresses over

725 pools and riffles are both over- or underestimated, or shear stress over pools is

726 underestimated and/or shear stress over riffles is overestimated, grains in pools will

727 still be more likely to be entrained than riffle grains. This difference in mobility may

728 not hold if pool shear stresses are overestimated and/or riffle shear stresses are

729 underestimated. However, in order to equalise the probability of entrainment from

730 pools and riffles under the standard Manning's n parameterisation, it is necessary

731 either to reduce the predicted pool shear stresses to a third of their current values, or to

732 increase the riffle shear stresses by 1.6. Under the low Manning's n parameterisation

733 pool stresses need to be reduced to a fifth of current values, or riffle shear stresses

734 need to be tripled. As such, our conclusions are valid across a range of scenarios,
735 despite the flow modelling being relatively poorly constrained.

736 **6. Discussion and conclusions**

737 Whilst previous research has identified differences in the frequency of tight and loose
738 particle structure in pool and riffle sequences (Clifford 1993; Sear 1996) and have
739 provided some evidence for lower critical entrainment thresholds for particles in pools
740 (Sear 1996) these have been based on rather limited datasets. The field data we report
741 demonstrate that grain-scale sediment properties vary between different units of a
742 riffle-pool sequence. In pools, grains have lower pivoting angles and higher exposure
743 (Table 2), which is inferred to be a consequence of looser sediment packing. In pool
744 exits and riffles, grains have higher pivoting angles and lower exposure as a result of
745 closer packing (Table 2). We have used the field data to parameterise Kirchner *et al.*'s
746 (1990) physically-based model of grain entrainment in order to predict distributions of
747 critical entrainment shear stress (τ_c) for grains in the different facies. These model
748 results confirm that τ_c is lowest for grains in pools; using model B, when $D/D_{50} = 1$,
749 τ_c^* in pools is 58% of τ_c^* in riffles. Previous efforts to parameterise a similar model
750 were speculative because of the inability to directly measure parameters such as
751 pivoting angle and grain exposure (Sear 1996). Hence our results provide more
752 detailed and accurate evidence for the existence of a feedback between bed fabric and
753 entrainment thresholds. Moreover, there is a clear and repeatable spatial component to
754 the distribution of critical entrainment thresholds.

755

756 Comparison between the flow model estimates (from different parameterisations of
757 the flow model) and the values of τ_c predicted by the grain entrainment model suggest

758 that sediment will be most mobile in the pools and least mobile in the pool exits. This
759 therefore provides a mechanism by which sediment is preferentially entrained from
760 pools, despite the fact that pools experience lower shear stresses than riffles. The
761 findings from the field data and modelling therefore go some way towards testing the
762 validity of the Differential Sediment Entrainment Hypothesis. Furthermore, our data
763 support the development of differential mobility between pools and riffles, without
764 the need for the velocity reversal that is typically assumed to be necessary for pool-
765 riffle maintenance (Booker *et al.*, 2001; Milan *et al.*, 2001).

766

767 However, there are important differences between the field data and the conceptual
768 model developed by Sear (1996), as outlined in Table 2. These differences principally
769 relate to the pool-tail. In his original model, Sear (1996) postulated the pool-tail as a
770 region of relatively fine sediment, low surface roughness and weakly developed bed
771 structure. The result was a region of lower critical entrainment thresholds (though
772 higher than those predicted for mid-pool regions). In this study, there are similarities
773 to Sear's model; the low surface roughness and finer sediment, but the overall effect
774 of these in addition to the presence of silt-clay mortar, is a higher critical shear stress
775 than he postulated.

776

777 The presence of a layer of fine sediment at and just below the surface of the bed, has
778 been described in studies of fine sediment infiltration (Frostick *et al.*, 1984; Lisle
779 1989; Sear *et al.*, 2008) and is a widely used measure of habitat impact by fisheries
780 biologists termed "embeddedness" (Sylte and Fischenich 2002). To date the role of
781 cohesive matrix material on critical entrainment thresholds has not been reported. In
782 Lisle's (1989) study the matrix was largely composed of sands. Moreover previous

783 research has tended to focus on the process of infiltration in relation to the impact on
784 biota (Sear *et al.*, 2008) or the development of stratigraphic and sedimentological
785 characteristics (Frostick *et al.*, 1984). In the pool exits, we show that mortaring has
786 increased values of $m (F_L/F_W)$ from a mean of 1.4 for grains without mortaring to 3.9
787 for grains with mortaring. However, the specific effect of mortaring on τ_c is difficult
788 to quantify because it will also affect other properties such as pivoting angle and
789 exposure. An indication of the potential effect of mortaring is given by model B.
790 Explicit incorporation of the effect of mortaring increases the predicted median τ_c for
791 pool exit grains by 47 % from 52.6 Pa to 77.4 Pa. Recent, independent confirmation
792 of the importance of mortaring comes from a study of critical entrainment thresholds
793 in ephemeral channels (Barzilai *et al.*, in review). In their study, an input of cohesive
794 silt/clay matrix material following bank erosion resulted in a measurable increase in
795 the shear stress required for initiation of bedload transport.

796

797 Our data have 1) demonstrated the important role of sediment structure in controlling
798 sediment entrainment, and 2) demonstrated statistically significant spatial variability
799 in sediment structure independent of bed material size and shape. We assume that the
800 development of sediment structure is controlled by the time varying exposure to
801 different hydraulic environments (Clifford 1993; Sear 1996; Haynes and Pender
802 2007), but we also recognise the importance of grain shape, and fine cohesive
803 sediment. Hodge *et al.* (2009b) and Komar and Li (1986) show that elongated
804 particles develop imbrication that results in higher bed roughness and pivot angles. In
805 this paper, we demonstrate for the first time, the additional effect of cohesive fine
806 sediment in mortaring framework particles. The formation of mortar in pool-tails is,
807 we hypothesize, due to downwelling flow on the upslope of the riffle (Storey *et al.*,

808 2003; Tonina and Buffington, 2007) that advects suspended sediment into the surface
809 interstices. The stability of this mortar in the presence of perennial flows is unknown.
810 However the effect on entrainment thresholds is significant and warrants further
811 research.

812

813 Whilst this study has focussed on the pool-riffle sequence, we hypothesize that similar
814 magnitudes of spatial variability in critical entrainment thresholds will exist between
815 bed fabrics in other contrasting hydraulic environments. In this work for example we
816 did not look at the lateral variations in sediment structure in bedforms, which might
817 be expected where pool asymmetry arises at bends. Similarly, the presence of
818 mortaring at or downstream of local inputs of cohesive fines is widely reported in the
819 fisheries management literature (Sylte and Fischenich 2002).

820

821 Due to the need to access the channel bed, measurements have necessarily been taken
822 whilst the bed was exposed. Our conclusions are therefore subject to the assumption
823 that perennial inundation will not significantly change the sediment structure; given
824 the magnitude and repeatability of the differences between the different facies over
825 time, significant changes are hypothesised to be unlikely, but this requires
826 verification. Furthermore, the importance of mortaring also assumes that the matrix
827 material is not flushed from the bed surface or infiltrated into the bed during
828 inundation. Hence, it will be important to understand the stability of cohesive matrix
829 materials before further conclusions can be made.

830

831 Significant research questions still remain as to the processes that result in the
832 documented differences in sediment structure. A complete understanding will need to

833 consider the interactions between hydraulics, sediment transport and channel
834 morphology that drive the formation and persistence of sediment structure.

835 **Acknowledgements**

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837 Geomorphology. Thanks to Steve Darby, Paul Carling and two anonymous reviewers
838 for their helpful and constructive comments on earlier drafts of this paper.

839 **Symbols**

840	A	grain area
841	C_D	drag co-efficient
842	C_L	lift co-efficient
843	D	grain diameter
844	d_t	maximum sheltering distance
845	d_u	distance of upstream sheltering grain
846	e	grain exposure
847	f	Darcy-Weisbach friction factor
848	F_D	drag force applied to a grain
849	F_d	measured horizontal force necessary to dislodge a grain
850	F_L	lift force applied to a grain
851	F_W	grain weight
852	g	acceleration due to gravity
853	h	grain height
854	m	value of F_L/F_W necessary for vertical entrainment
855	p	grain projection
856	R	hydraulic radius
857	s	weighting quantifying grain sheltering
858	$u(z)$	velocity at height z
859	W	grain width
860	z	elevation above the bed
861	z_0	roughness height
862	β	local bedslope
863	κ	von Kármán's constant
864	ρ	density of water
865	ρ_s	density of sediment
866	τ	shear stress
867	τ_c^*	dimensionless critical entrainment shear stress
868	τ_c	critical entrainment shear stress
869	Φ	grain pivoting angle
870		

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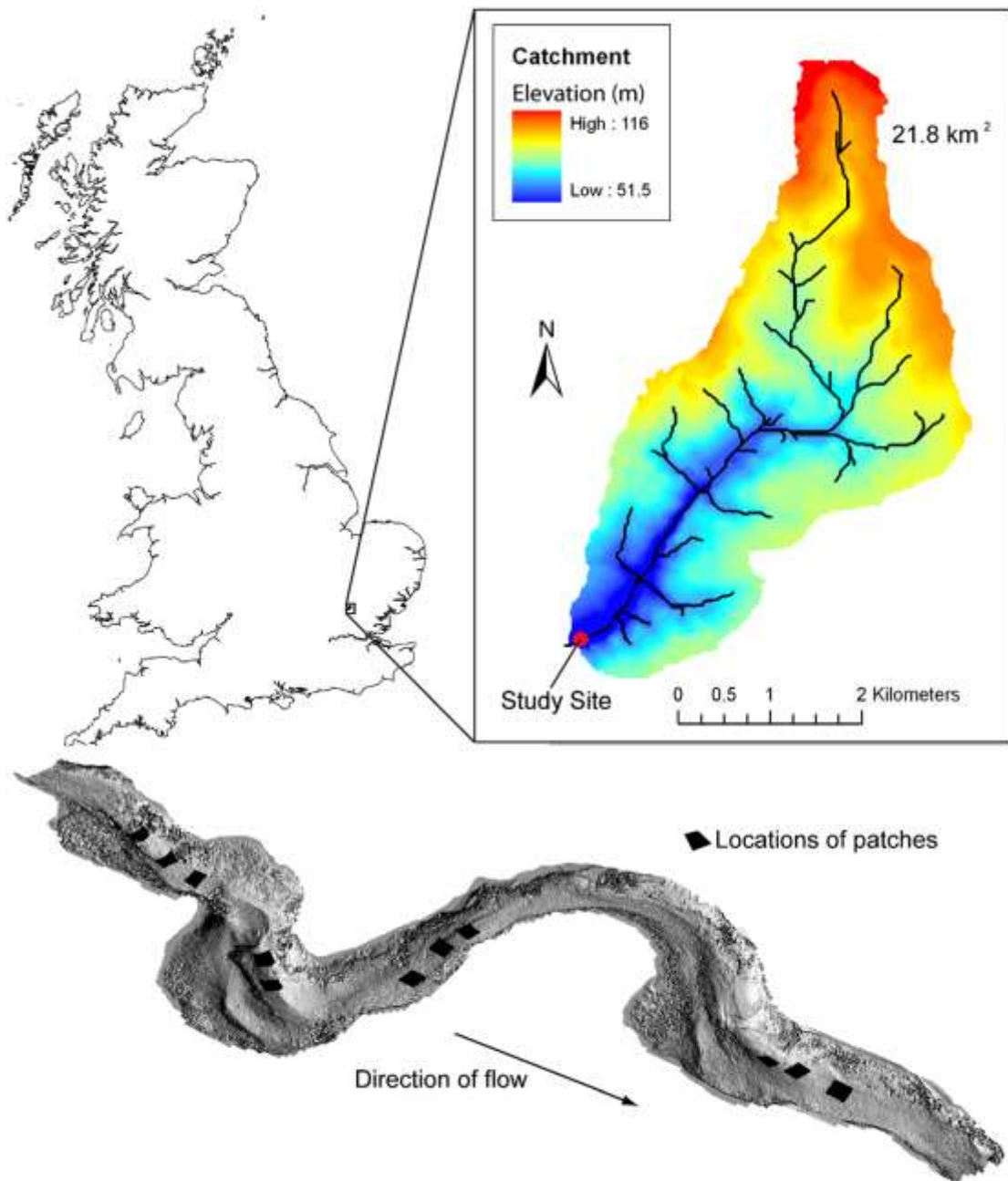
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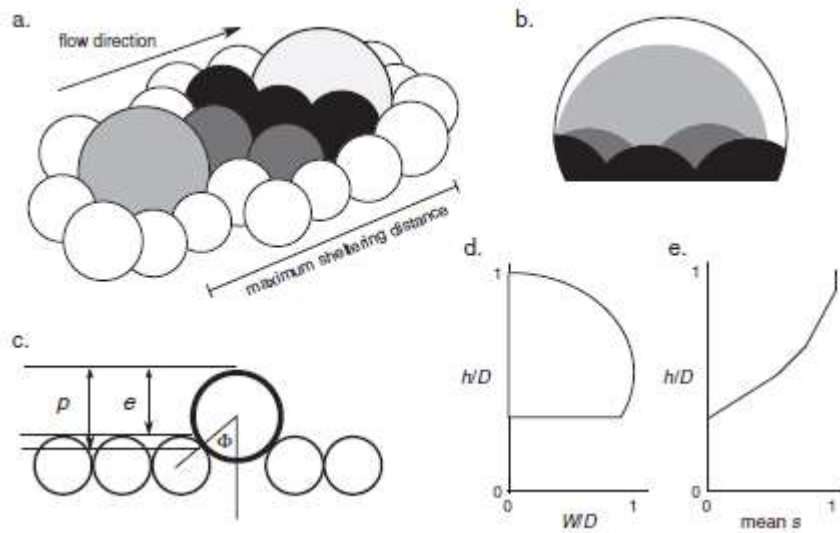
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1056 Figure 1: Location and topography of the 21.8 km² Bury Green Brook catchment in
1057 Essex, UK. Lower figure shows the study site reach of approximately 80 m (along
1058 thalweg) and the locations of the 1 m x 1 m patches which were scanned at high
1059 resolution. This figure is available in colour online.

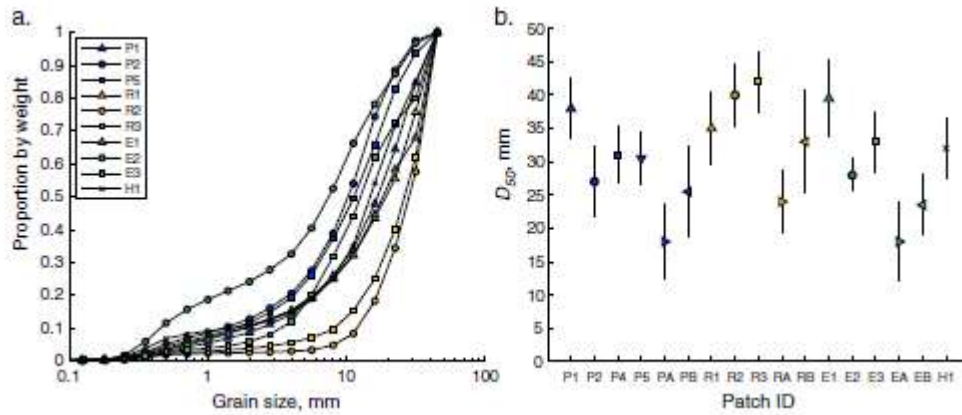
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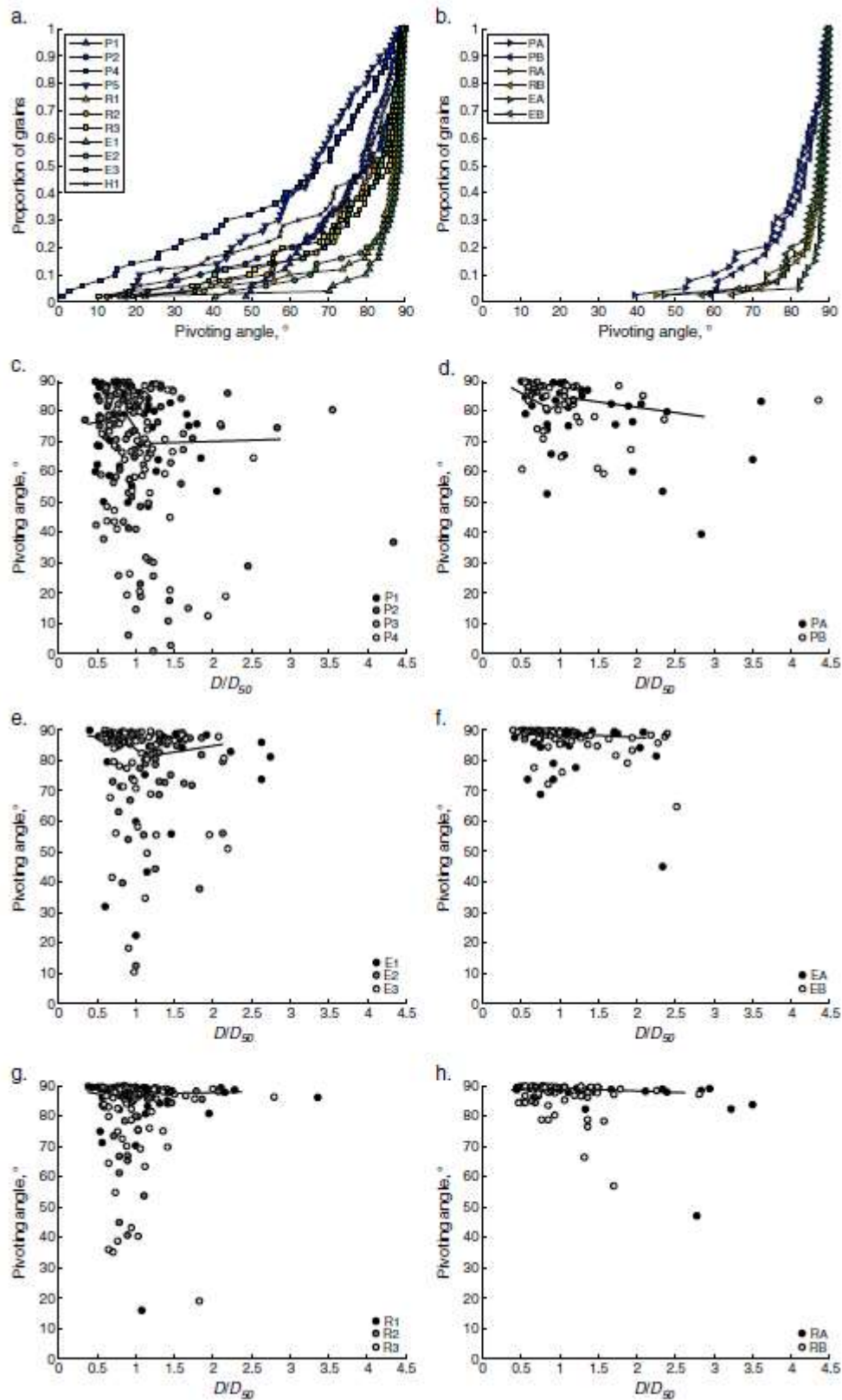
1062 Figure 2: Methods of measuring grain exposure: a) Diagram showing grain for which
 1063 exposure is being measured (white, thick outline) and sheltering grains. Sheltering
 1064 grains are shaded according to their upstream distance relative to the maximum
 1065 sheltering distance; darker grains exert a larger sheltering effect than lighter grains
 1066 and white grains have no impact. b) Face of grain shaded according to upstream
 1067 distance of sheltering grain, i.e. the value of weighting s . White areas have no shelter
 1068 ($s = 1$), whereas black areas are highly sheltered ($s \sim 0$). c) 1D measurements of grain
 1069 protrusion (p) and exposure (e). d) Variation in the width (W) of the exposed grain in
 1070 (b) with height below the top of the grain (h). W and h are normalised by grain
 1071 diameter (D). e) Variation in the width-averaged sheltering value (s) on the grain face
 1072 in (b) with height. Sheltering varies from 1 (complete exposure over the maximum
 1073 sheltering distance) to 0 (area of the grain is in contact with sheltering grains).

1074



1075

1076 Figure 3: a) GSD of the surface layer of each 2009 patch (except P4), expressed as the
 1077 weight of size fractions of a sifted surface sample. b) D_{50} of the coarse fraction of all
 1078 2006 and 2009 patches, calculated from all grains used for pivoting and lift
 1079 measurements. Grains were selected using a grid. 95% error bars are also shown; error
 1080 bars are calculated from the standard error of the median (Mosteller and Tukey, 1977)
 1081 as $D_{50} \pm 1.253 \times 1.96 \times (\sigma/\sqrt{n})$, where σ is the standard deviation and n is the number
 1082 of grains. This figure is available in colour online.

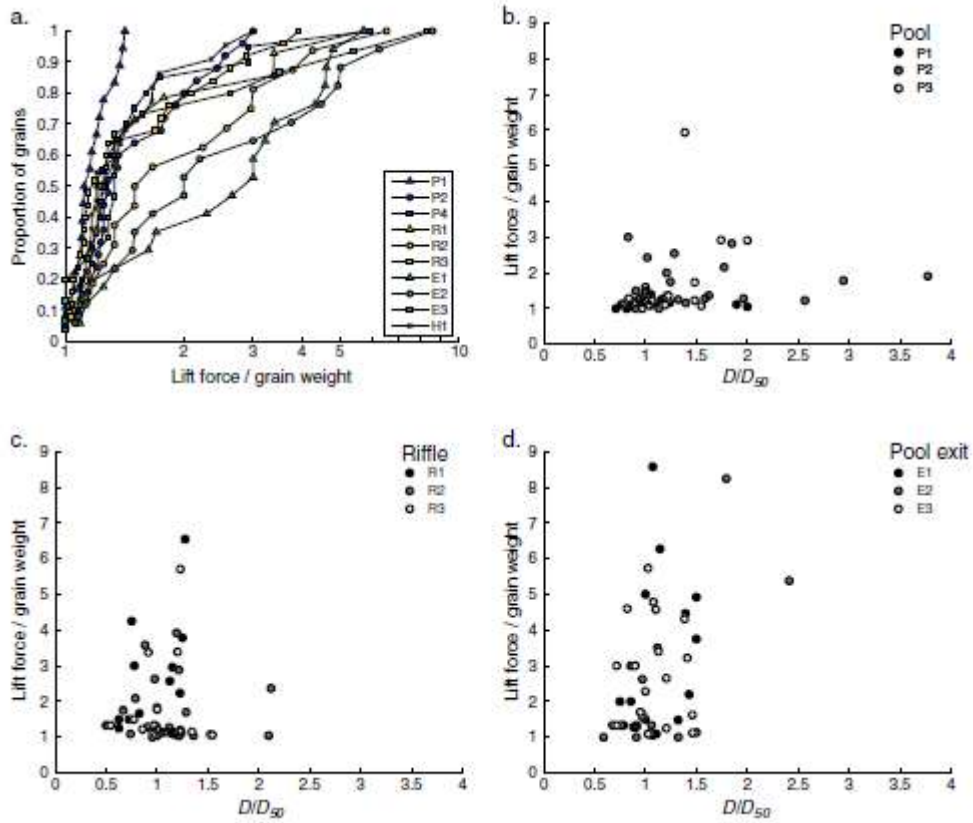


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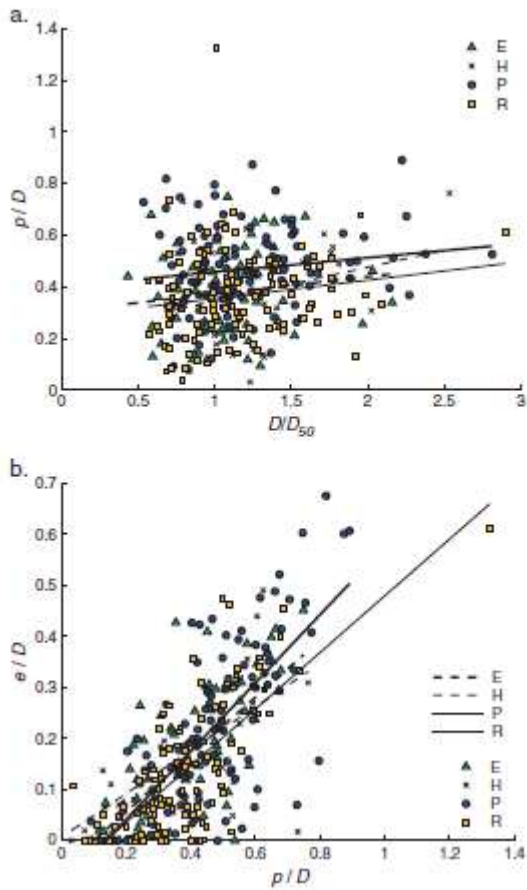
1084 Figure 4: a and b) Cumulative distributions of grain pivoting angles from all patches

1085 from (a) 2009 and (b) 2006. c to h) Distributions of grain pivoting angles as a function

1086 of grain b-axis length. Data are from (c and d) pools, (e and f) pool exits and (g and h)
 1087 riffles. Data are from (c, e and g) 2009 and (d, f and h) 2006. Within each subplot,
 1088 data points are shaded according to which patch they were measured from. The line
 1089 shows the 50th percentile fitted to grain size bins containing at least 30 grains. This
 1090 figure is available in colour online.

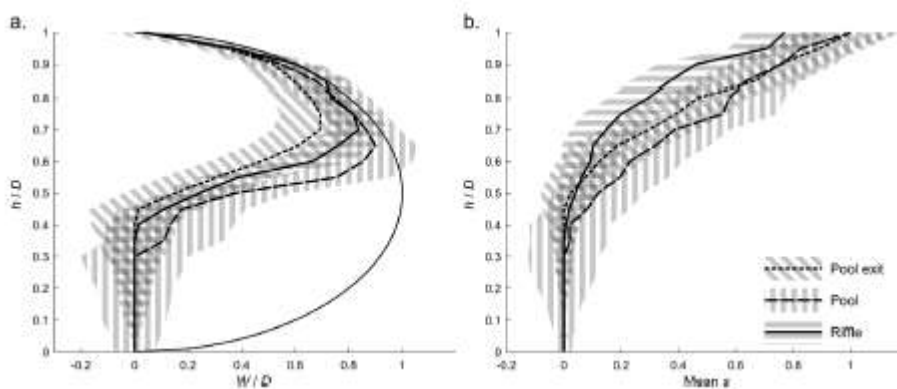


1091
 1092 Figure 5: a) Cumulative distributions of lift force per unit grain weight, m , for the
 1093 different patches. b – d) Distributions of m as a function of D/D_{50} for the different
 1094 facies. Different patches are plotted in different shades. This figure is available in
 1095 colour online.



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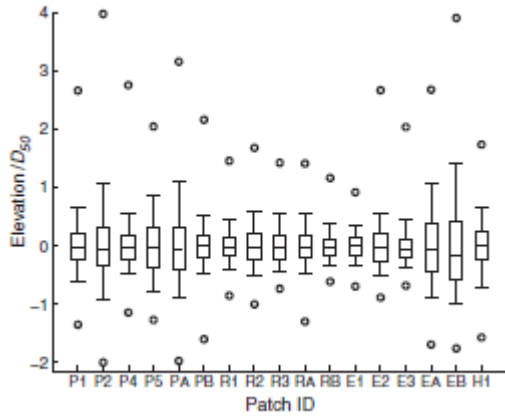
1097 Figure 6: a) Relationship between relative protrusion (p/D) and D/D_{50} . b) Relationship
 1098 between relative exposure (e/D) and p/D . Linear regression lines are fitted to each
 1099 dataset. This figure is available in colour online.



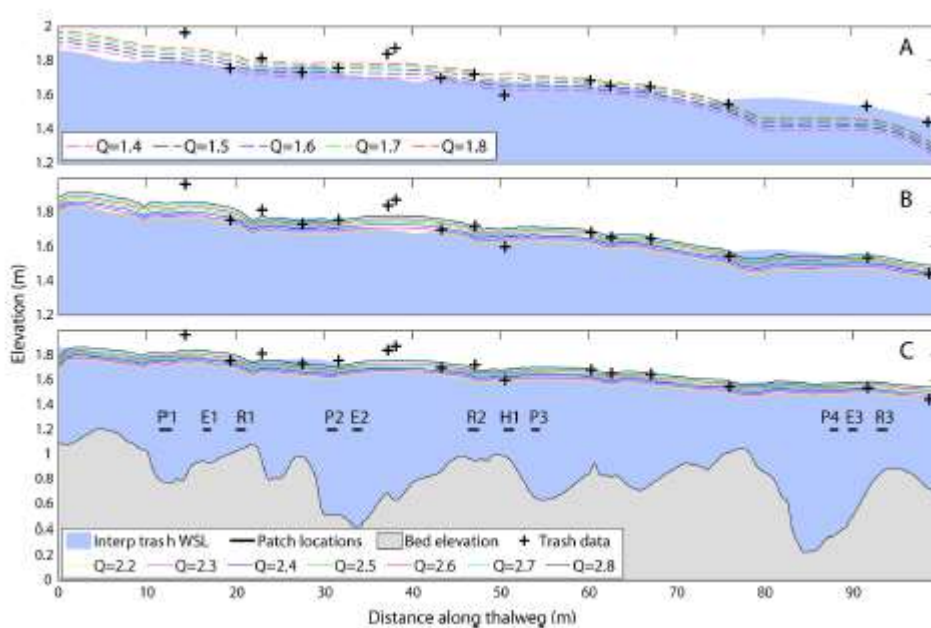
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1101 Figure 7: a) Median distributions of grain exposure width (W/D) as a function of
 1102 elevation (h/D). For each value of h/D , the plotted value of W/D is the median of W/D
 1103 for all grains from that facies. Black thin line shows W/D for a completely exposed
 1104 sphere. b) Median distributions of sheltering weighting (s) as a function of h/D . For

1105 each grain, s is initially calculated as the mean s across the grain at each value of h/D .
 1106 This plot shows the median of the mean values from all grains within a facies. Both
 1107 plots show data from pool, pool exit and riffle facies. 95 % error bands around the
 1108 median are calculated as $1.96 \times$ standard error of the median.

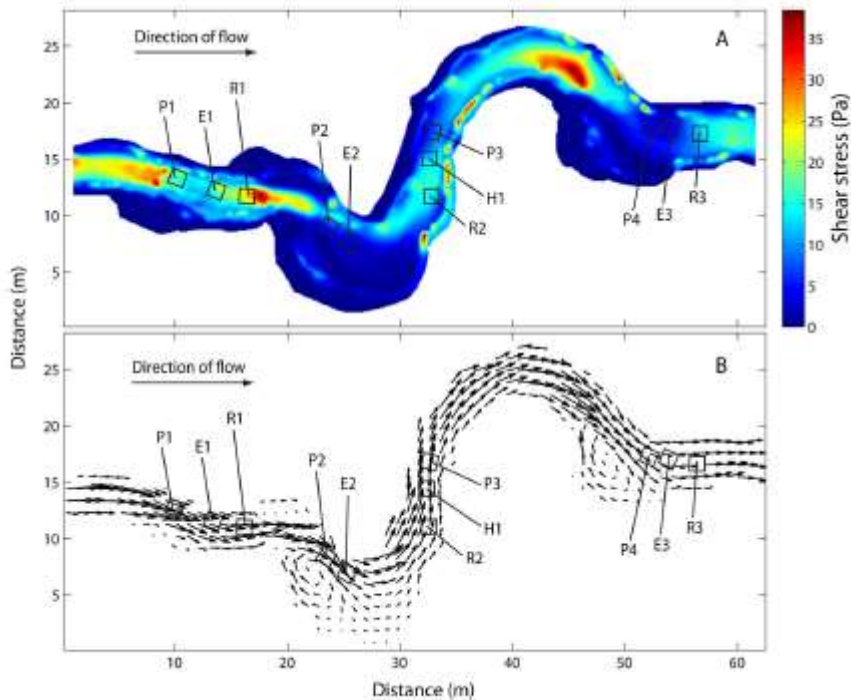


1109
 1110 Figure 8: Distributions of surface elevations from all patches. Boxplots show the 25th
 1111 to 75th percentiles, dashed line is the median, whiskers show the 5th to 95th percentiles
 1112 and circles show the maximum and minimum. All elevations are normalised by the
 1113 patch D_{50} (in Figure 3b), and all patches have a mean elevation of 0.

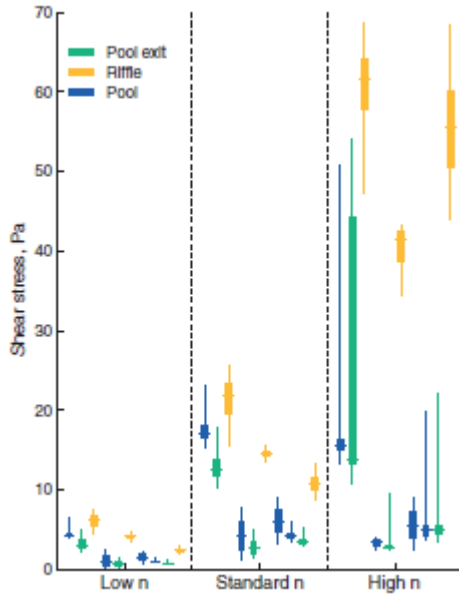


1114
 1115 Figure 9: Channel topography along the thalweg of the reach, showing location of
 1116 patches. The water surface interpolated from the trash markers is shown in blue, and

1117 the trash marks as crosses. Water surfaces modelled using Hydro2de and discharges
 1118 between 2.2 and $2.8 \text{ m}^3\text{s}^{-1}$ are shown for A) low and B) standard Manning's n
 1119 parameterisations. For C) high Manning's n parameterisations discharges between 1.4
 1120 and $1.8 \text{ m}^3\text{s}^{-1}$ are shown. Best fits are given by $2.6 \text{ m}^3\text{s}^{-1}$ (low n) and $2.5 \text{ m}^3\text{s}^{-1}$
 1121 (standard n). This figure is available in colour online.

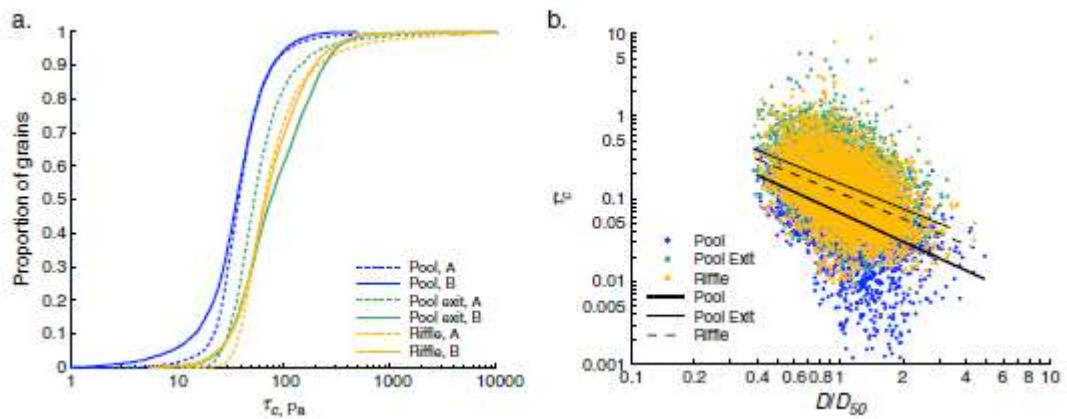


1122
 1123 Figure 10: The spatial distribution of shear stress and flow velocity in a model run
 1124 with standard n and a discharge of $2.5 \text{ m}^3\text{s}^{-1}$. Note the unidirectional and relatively
 1125 faster flow over the riffles. Squares show locations of field measurements. This figure
 1126 is available in colour online.



1127

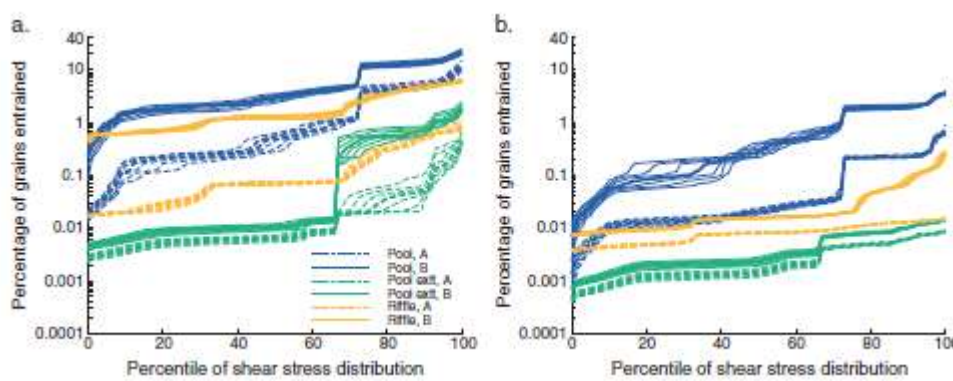
1128 Figure 11: Distributions of shear stress across patches under different
 1129 parameterisations of Manning's n . For each parameterisation the discharge shown is
 1130 that which best reproduces the trash surface (low n , $Q = 2.6 \text{ m}^3 \text{ s}^{-1}$; standard n , $Q = 2.5$
 1131 $\text{m}^3 \text{ s}^{-1}$; high n , $Q = 1.5 \text{ m}^3 \text{ s}^{-1}$). Each distribution represents the range of shear stress
 1132 from a single patch (thin line shows minimum to maximum, thick line shows
 1133 interquartile range and horizontal line shows the median). For each parameterisation
 1134 patches are plotted from left to right in the downstream order (P1, E1, R1, P2, E2, R2,
 1135 P3, P4, E3, R3). This figure is available in colour online.



1136

1137 Figure 12: a) Distributions of critical entrainment shear stress (τ_c) for grains in pool,
 1138 pool exit and riffle facies, as predicted by grain entrainment model runs A and B. See

1139 text for model descriptions. b) Relationship between D/D_{50} and τ_c^* for grains from
 1140 model B runs with pool, pool exit and riffle parameter values. Linear regressions have
 1141 equations: pool grains, $1.6 \times 10^{-11} D^{0.42}$; pool exit grains,
 1142 $1.6 \times 10^{-11} D^{0.42}$; riffle grains, $1.6 \times 10^{-11} D^{0.42}$.
 1143 p-values for all regressions are < 0.0001 , and the gradient for the pool exit and riffle
 1144 regressions are not significantly different to -1 ($\alpha=0.05$). This figure is available in
 1145 colour online.



1146
 1147 Figure 13: Comparison between the distributions of critical entrainment shear stress
 1148 (τ_c) predicted from the field data and the distributions of shear stress predicted by the
 1149 CFD model using a) standard and b) low parameterisation of Manning's n. Each plot
 1150 shows the percentage of grains that would be entrained by different percentiles of the
 1151 CFD shear stress distribution. Distributions of τ_c are predicted for grains in pool, pool
 1152 exit and riffle facies using both models A and B. Results are shown for all seven
 1153 discharges used in the flow model; the bold line shows the optimum discharge. This
 1154 figure is available in colour online.

1155 **Tables**

1156 Table 1: Parameters needed for the grain entrainment model, and the methods used to

1157 derive parameter values from the field data. Only the 2009 data are used. (A) and (B)

1158 refer to the two model variants.

Parameter	Method	Parameter values
Grain diameter (D)	Random sampling from lognormal fit to patch GSDs. Equal proportion of grains are selected from each patch within the facies.	Mean/variance of lognormal distribution (mm) Pool: 38/221, 32/243, 34/150, 32/109 Pool exit: 41/322, 29/59, 37/180 Riffle: 40/293, 44/253, 46/223
D_{50}/D_{84}	Taken from same patch as D	D_{50}/D_{84} (mm) Pool: 38/51, 27/46, 31/45, 30.5/42 Pool exit: 39.5/57, 28/37, 33/50 Riffle: 35/55, 40/58, 42/60
Pivoting angle (Φ)	Identify size class for grain (D/D_{50} , as in Figure 4), randomly select percentile (n), and interpolate value of Φ for that percentile from field data	Percentile distributions as in Figure 4.
Lift force multiple (m)	(A) Resistance to lift not included (B) Randomly select percentile, and interpolate that percentile from distribution of all values of m from that facies.	$m = 1$ Use distributions in Figure 5
Grain protrusion (p)	(A) Randomly sample from normal distribution fitted to the field data from that facies (B) 100- n^{th} percentile of normal distribution fitted to field data	Mean/standard deviation of normal distribution (-) Pool: 0.47/0.17 Pool exit: 0.38/0.16 Riffle: 0.37/0.17
Grain exposure (e)	Calculated from the regression between p/D and e/D , with normally distributed errors E : $e/D = a p/D + b + E$	a/b /standard deviation of E (-) Pool: 0.67/-0.09/0.11 Pool exit: 0.56/-0.06/0.09 Riffle: 0.56/-0.08/0.09

1159

1160 Table 2: Summary of trends in field measurements and DTM analysis

Bedform		Riffle	Pool head	Pool	Pool exit
Grain size	Trend	Larger	Smaller	Smaller	Intermediate
	D_{50} (mm)	35 - 42	32	27 - 38	28 - 37
	Sear (1996)	<i>Largest</i>	—————▶		
Pivoting angle	Trend	High	Intermediate	Low	Highest
	Φ (°) ^a	76	70	62	83
Lift force	Trend	Intermediate	Low	Low	High
	mean m (F_L/F_W)	1.9	1.6	1.5	2.7
Grain exposure	Trend (W/D):	Intermediate	n/a	High	Low
	Trend (s):	High	n/a	Low	Intermediate
	Sear (1996)	<i>Low</i>	—————▶		
Surface roughness	Trend	Low	Intermediate	High	Low
	Range/ D_{50}	0.73 – 1.10	1.36	0.99 – 2.01	0.72 – 1.08
Entrainment shear stress	Trend	High	n/a	Low	High
	median τ_c (Pa) ^b	68.1	n/a	36.2	77.4
	Sear (1996)	<i>High</i>	—————▶		

1161 ^aPivot angle predicted for $D/D_{50} = 1$ from fit of equation 10 to the data.1162 ^bPredicted using model B.