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Stéphane Bertin, Jane Groom, Heide Friedrich

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1 **Assessing intra-bar variations in grain roughness using close-range photogrammetry**

2 **Jane Groom** ([jgro800@aucklanduni.ac.nz](mailto:jgro800@aucklanduni.ac.nz)),

3 **Stéphane Bertin** ([s.bertin@ymail.com](mailto:s.bertin@ymail.com)) and

4 **Heide Friedrich** ([h.friedrich@auckland.ac.nz](mailto:h.friedrich@auckland.ac.nz))

5 Department of Civil and Environmental Engineering, University of Auckland, New Zealand.

6

7 **ABSTRACT**

8 Evidence of downstream fining in sediment size along the length of a gravel bar has  
9 frequently been observed. However, there is limited quantitative information on the variation  
10 of other roughness statistics. Developments in high-resolution topographic data acquisition  
11 provide the opportunity for assessing roughness variations along and across a gravel bar,  
12 to quantify existing theoretical observations of bar sorting. Here, close-range  
13 photogrammetry is used for the first time to assess intra-bar variations in roughness, at 14  
14 different locations on a single gravel bar in the Whakatiwai River, New Zealand. An  
15 extensive range of roughness parameters are used, including the standard deviation of  
16 elevations, skewness, kurtosis, inclination index, and horizontal roughness lengths from  
17 second-order structure functions. A reduction with distance down bar was found in all  
18 roughness parameters, except skewness, along with a decrease in the variability of the data  
19 at the bar tail for all parameters. Lateral variation in roughness parameters was also  
20 assessed, showing evidence of an increase in roughness parameters with distance from the  
21 water edge. These findings can be used to validate and calibrate existing flow resistance  
22 equations and morphodynamic models. General trends in roughness statistics indicate  
23 coarser sediment at the bar head and near the river bank. These trends reflect the formative  
24 flows and are used to infer sedimentation patterns, which suggest that the gravel bar

25 undergoes development through lateral accretion. Although complexities in the  
26 sedimentation patterns are evident, due to multiple cycles of erosion and deposition, a  
27 greater understanding of these patterns is needed for the implementation of successful river  
28 management for this river, and others.

## 29 **Keywords**

30 Grain-roughness; gravel bar; fluvial morphology, close-range photogrammetry, DEM

## 31 **INTRODUCTION**

32 Fluvial systems demonstrate reach-scale patterns in sedimentation, including downstream  
33 fining (i.e., a reduction in grain size) (Sternberg 1875). Although there is less published  
34 research on intra-bar variability, variations in sediment characteristics (e.g., size, sorting and  
35 packing) across gravel bars contribute to bar morphology and, in turn, channel morphology  
36 (Ashworth and Ferguson 1986; Hardy 2006; Rice and Church 2010). The formation of bars  
37 occurs from spatial variations in sedimentation, including, but not limited to, lateral accretion  
38 and sediment accumulation due to flow convergence, which can result in down bar fining of  
39 sediment (Leopold and Wolman 1957; Parker 1975; Nanson 1980; Bluck 1982; Leopold  
40 1992; Ashworth 1996; Bluck 1976; Bridge 2003; Burge 2006). Due to feedbacks between  
41 channel morphology, sedimentation and flow properties, the presence of gravel bars can  
42 alter flow properties and roughness at different scales, including reach, bar, and grain scale  
43 (Church and Jones 1982; Ashworth 1996; Bridge 2003; Church 2006; Raven et al. 2009;  
44 Bertoldi et al. 2009).

45 Roughness, resulting from these sedimentation patterns, is an important aspect within a  
46 fluvial system due to its influence on flow properties (including velocity and turbulence),  
47 sediment transport, and local ecology (Aberle and Nikora 2006; Hodge et al. 2009a; Baewert  
48 et al. 2014; Curran and Waters 2014). Estimations of roughness are important inputs for

49 hydraulic and morphological models, along with models to determine the flow resistance  
50 within a channel (Aberle and Smart 2003; Tuijnder and Ribberink 2012).

51 Flow resistance results from forces that act on, and within, a flow to resist motion (Powell  
52 2014), with various sources of energy loss in alluvial rivers. To calculate the flow's energy  
53 loss, hydraulic parameters such as velocity, depth, slope and boundary shear stress must  
54 be predicted or calculated. Generally, there are three flow resistance equations that are  
55 used in fluvial research; Darcy-Weisbach, Chezy and Manning equations, which all use  
56 roughness coefficients. The determination of these roughness coefficients is crucial for the  
57 calculation of flow resistance. However, determining the values of the coefficients is fraught  
58 with subjectivity, and thus they are often the main source of error in estimates of discharge  
59 and flow resistance (Powell 2014). Choosing the correct equation in flow modelling can be  
60 problematic, as an increasing number of modelling software programs calculate flow  
61 resistance automatically, without clarifying how it is calculated (Powell 2014). For example,  
62 flow modelling packages still use Manning's  $n$  as a roughness coefficient, although it has  
63 been identified as having many flaws, and there have been calls to move to a more robust  
64 alternative roughness coefficient (e.g., quantitative roughness parameters such as the  
65 standard deviation of elevations) (Ferguson, 2010; Powell 2014).

66 Roughness is a term that is frequently used in literature, but is rarely explicitly defined, which  
67 causes confusion (Smith 2014). Roughness is often used as a synonym for flow resistance,  
68 which suggests that roughness is a property of the flow rather than of a surface. Instead,  
69 we define grain roughness throughout this manuscript as the microtopography of the  
70 surface, resulting from the topography of individual grains; therefore roughness is a property  
71 of the surface, with a pronounced effect on flow resistance.

72 Our understanding of bed roughness (i.e., microtopography of the surface) is facilitated by  
73 the development of technologies for the acquisition of high-resolution data. This includes (i)

74 aerial photosieving (Carbonneau et al. 2004), which although it can cover a large spatial  
75 scale, has been found to overestimate grain size; (ii) laser scanning (Milan et al. 2007;  
76 Entwistle and Fuller 2009; Heritage and Milan 2009; Brasington et al. 2012), which is  
77 expensive and time consuming; and (iii) structure-from-motion on unmanned aerial systems,  
78 which enables for the spatial variability of roughness to be assessed and inputted into  
79 morphodynamic models, although noise from reconstructions of up to 10 mm and blurry  
80 images are problematic (Vazquez-Tarrio et al. 2017). The technique of close-range  
81 photogrammetry (Bertin and Friedrich 2016) uses consumer grade cameras (i.e.,  
82 inexpensive), which can provide millimeter accuracy to address these aforementioned  
83 issues.

84 An increase in availability of large topographic datasets from these methods has led to an  
85 expansion in the literature of information about the grain size of the surface, which is used  
86 for calculating bed shear stress and estimating sediment transport (Pearson et al. 2017).  
87 Further, these large topographic datasets have resulted in the improved quantification of  
88 grain-roughness parameters. This includes bed-elevation moments from digital elevation  
89 models (DEMs), such as standard deviation of elevations, skewness, and kurtosis. These  
90 improvements signal a shift away from the previous use of roughness coefficients,  
91 percentiles of grain size or roughness heights calibrated from flow measurements (Wilcock  
92 1996; Smart et al. 2004; Aberle and Nikora 2006).

93 The aim of this paper is to obtain an improved understanding of bar-scale variations in grain-  
94 roughness parameters. There is little information regarding the grain-scale variations of  
95 surface structure and roughness within gravel surfaces (Bertin and Friedrich 2016). This is  
96 despite knowing that these aspects are key influences on flow resistance, sediment  
97 transport, and ecohydraulics (Aberle and Nikora 2006; Baewert et al. 2014; Curran and  
98 Waters 2014). This paper has three objectives:

99 1. To assess grain-roughness variability across the gravel bar, using an extensive range of  
100 roughness parameters; although bar-scale sorting is well documented (Rice and Church  
101 2010), there is little quantification of this observation. Further, surface roughness of bars is  
102 rarely uniformly distributed and its heterogeneity is of great interest (Smith, 2014).

103 2. To examine roughness parameters and grain size relationships, as research has  
104 investigated the relationship between grain size and the standard deviation of elevations (a  
105 common proxy for grain size). The influence of multiple factors including survey error, bed  
106 composition (e.g., packing, particle shape, sorting) and scale of roughness has been  
107 explored (Pearson et al. 2017), but further work is needed to understand and quantify these  
108 factors.

109 3. To understand if empirical roughness parameterization can lead to inferences concerning  
110 sedimentation patterns, which can provide insights into the physical processes that influence  
111 surface morphology (Hodge et al. 2009).

## 112 **METHODOLOGY**

### 113 Data collection

114 Data were obtained from the Whakatiwai River; a small gravel-bed stream in the Whakatiwai  
115 catchment (~ 1675 ha), which is located in north east North Island, New Zealand (Fig. 1).

116 The stream has limited protection or management schemes (Hauraki Council 2011), apart  
117 from stopbanks (levees) upstream and downstream of the gravel bar studied in this  
118 investigation. Previously, cyclone Wilma (January 28-29<sup>th</sup> 2011) resulted in the stream  
119 undergoing significant lateral erosion in the stopbanked reaches, with calls from the  
120 community for management practices to be put in place. Surrounding areas of the stream  
121 mouth have high significance to the local iwi (Māori people), with urupa (burial ground) and  
122 waahi tapu (sacred spiritual areas), and thus the local community is concerned with their

123 protection. Recent channel protection works include the insertion of gabion baskets,  
124 although these are thought to be of limited effect due to channel movement (Hauraki Council  
125 2011).

126 Our field observations at the time of data collection include bank erosion and evidence of  
127 animal activity on exposed gravel bars upstream of the study site, due to the surrounding  
128 farmland. This study focuses on an exposed gravel bar, located 300 meters upstream from  
129 the stream mouth. This gravel bar was chosen due to ease of accessibility with equipment  
130 from the road, and because previous field investigations using close-range photogrammetry  
131 were also undertaken at this site (Bertin and Friedrich 2016). Upstream areas of the bar  
132 were vegetated with clusters of dense pampas grass, and there was a change in elevation  
133 towards the water edge, with a slope vegetated by grass. The gravel bar selected for this  
134 investigation did not display signs of animal activity or disturbance and was opposite a rock  
135 revetment structure (Figs. 1C, 2A, 2B). The bar is not surrounded by accessible farmland,  
136 but instead is attached to a densely vegetated bank (Fig. 2). Google Earth images provide  
137 an indication to the evolution of this gravel bar over time, with the apparent propagation of  
138 the bar downstream (Fig. 2).

139 A 30 meter tape measure was placed along the bar, and care was taken to only walk along  
140 this transect in order to not destroy natural sedimentation patterns, and measurement  
141 locations were placed either side of the transect, on non-disturbed areas. Measurement  
142 locations (Fig. 3), termed patches herein, were partially systematically chosen, covering  
143 down bar and lateral patterns, although they were not evenly spaced (due to the deliberate  
144 attempt to avoid vegetated areas). Distances between patches were measured with a tape  
145 measure in the field, and later verified using a scaled orthophoto of the bar (Fig. 3). The  
146 orthophoto of the bar was taken using GoPro cameras at a height of 2 meters above the  
147 gravel surface. Subsequently, for analysis, the gravel bar was split into three sections every  
148 10 meters down the bar, differentiating between bar head, bar center and bar tail regions

149 (Fig. 3), similar to the method using in Rice and Church (2010) whom evaluated grain size  
150 variability by choosing sites that were representative of dominant textural facies.

151 At each patch, surface structure and grain size were measured using close-range digital  
152 photogrammetry (Fig. 1). Here, two Nikon D5100 cameras with Nikkor 20 mm lenses in  
153 tandem (16.4 Mpixel, 23.6 x 15.6 mm<sup>2</sup> sensor size), were used to take photos of the gravel  
154 surface. The cameras were calibrated in the laboratory prior to accessing the field (see  
155 analytical methods). Then the camera rig (horizontal metal frame) was kept in a wooden  
156 transportation box in order to reduce any movement in the camera set up during travel to  
157 the field. This has been found to have minimal disturbance to the (pre-calibrated) cameras  
158 and provide adequate results for high-quality DEMs with vertical accuracies, determined  
159 with a 3D-printed gravel bed and represented by the mean unsigned error between  
160 measurements and true values, of less than 1 mm (Bertin and Friedrich 2016). Once in the  
161 field, the camera rig was gently put on top of two tripods, placed ~1 m apart, and screwed  
162 securely in place. The cameras were at an approximate height of 75 cm from the gravel  
163 surface, as determined from a setup selection in the laboratory. Finally, two laptops were  
164 attached by cables to each camera, in order to remotely capture the photographs of the  
165 surface. Further details into the field-use of close-range photogrammetry are found in Bertin  
166 and Friedrich (2016).

167 A repeat calibration was completed in the field, as transporting the stereo setup is critical,  
168 and this provided the opportunity to determine the suitability of field calibration. Evaluation  
169 of the maximum field rectification error provided lower values of 0.47 pixel, compared to 0.88  
170 for the pre-calibrated laboratory calibration. Thereby the decision was made to use the field  
171 calibration for analysis, motivated by the smaller rectification error.

172 Analytical methods



173 Surface grain size (Table I) was subsequently obtained through the software Basegrain®,  
174 whereby a single photograph is used to generate a grain-size distribution for the patch  
175 (Detert and Weitbrecht 2012; Stähly et al. 2017). The minimum grain size sampled is a  
176 function of the pixel size on the gravel, with previous work indicating the need for a least 23  
177 pixels for effective grain identification (Graham et al. 2010). With an approximate pixel size  
178 of 0.19 mm, this means that grains larger than 4.5 mm were directly accounted for using  
179 Basegrain®. As recommended by previous authors, measured grain-size distributions were  
180 empirically corrected, with an assumption of 10% fine sediment not accounted for during  
181 detection for all patches (as per Ruther et al. 2013). Characteristic grain sizes of the bed-  
182 surface material were determined for all patches examined (Table I). The median grain size  
183 of the bed-surface material ( $d_{50}$ ) varies between 15 mm and 25.3 mm, and the coarsest  
184 fraction of sediment ( $d_{90}$ ) ranges between 32.2 mm and 64.4 mm (Table I).

185 Calibration parameters necessary for accurate DEMs with photogrammetry were obtained  
186 using images of a chequerboard and Bouquet's (2010) calibration toolbox in Matlab®, which  
187 provide both intrinsic (e.g., camera) and extrinsic (e.g., setup) parameters. Based on  
188 calibration data, obtained images of the gravel patches were rectified (maximum error < 1  
189 pixel), through which corresponding pixels in the two overlapping images are on the same  
190 scanline (i.e., same vertical coordinate). Stereo-matching was completed on the rectified  
191 images using Gimel'farb's (2002) symmetric dynamic programming stereo algorithm (SDPS)  
192 to produce point clouds of elevation data. Point clouds were first interpolated onto regular  
193 grids of 0.2 mm spacing, before being interpolated onto a 1 mm spacing grid (i.e. a raster  
194 DEM), resulting in less bias when calculating surface metrics in comparison to using non-  
195 uniform elevation data (Hodge et al. 2009). Using the mean elevation difference parameter  
196 (Hodge et al. 2009b), outliers were identified and replaced using bi-cubic spline interpolation.  
197 DEMs were normalized to a mean bed level of zero, and subsequently rotated to align with  
198 the flow direction (Hodge et al. 2009). Flow direction was determined by eye in the field,

199 based on channel observations and grain imbrication (Laronne and Carson 1976; Millane et  
200 al. 2006; Bertin and Friedrich 2016). The majority of each patch was vegetation free, and  
201 several overlapping DEMs were merged in order to generate patch sizes of > 1 m in length.  
202 However, in the case of some patches (e.g., bar head site P03, and bar center sites P06  
203 and P07), the presence of vegetation was removed from the patch, resulting in a smaller  
204 DEM, labelled with the letter A. For P03, two DEMs were made, on either side of the  
205 vegetation, and labelled A and B. For these patches, where vegetation was present, the  
206 smaller DEMs were used for analysis.

207 Before surface metric calculation, DEMs were all detrended, first using a bi-linear method  
208 and subsequently using a moving-window method. Bi-linear detrending removes the  
209 influence of riverbed slope or experimental setup misalignments (Bertin and Friedrich,  
210 2016). Moving-window detrending removes large-scale surface distortions larger than the  
211 cluster size for that patch, such as peaks and troughs resulting from bed undulations. As  
212 proposed in Smart et al. (2002), the trend surface corresponding to bed undulations was  
213 estimated over a grid with point spacing  $1.25 \times d_{90}$ , with the elevation of grid points measured  
214 by averaging DEM data points within a circle of diameter  $2.5 \times d_{90}$  centered on the grid point,  
215 and removed from the measured DEMs before analysis. Using a moving-window detrending  
216 method enables the grain topography to be solely considered due to the removal of  
217 bedforms, thereby subsequent roughness parameters determined from DEMs are  
218 representative of grain-scale roughness (i.e., the microtopography of the surface). Analysis  
219 of grain-scale roughness is further suitable due to the size of the patches investigated, as  
220 research has suggested larger patch sizes may be required for thorough analysis of larger  
221 scale bed undulations (Powell et al. 2016).

222 Surface metrics were calculated for each patch to assess variations in surface structure  
223 across the gravel bar. First, standard deviation ( $\sigma_z$ ) and skewness ( $S_k$ ) of bed elevations  
224 were determined from probability distribution functions (Equ. 1) to characterize bed

225 roughness (Aberle and Nikora 2006). These metrics were chosen to provide an indication  
 226 of the vertical roughness length ( $\sigma_z$ ) and water -working ( $S_k$ ) (Aberle and Smart 2003; Noss  
 227 and Lorke 2016; Aberle and Nikora 2006; Coleman et al. 2011). Skewness is a measure of  
 228 the degree of asymmetry of the probability distribution function. Positive values are indicative  
 229 of a water-worked, and armored, surface (Coleman et al. 2011; Bertin and Friedrich 2014)  
 230 because of coarse grains that form the surface, and the fact that the magnitude of surface  
 231 deviations below the mean is reduced by fine grains filling surface depressions (Nikora et  
 232 al. 1998; Aberle and Nikora 2006).

$$233 \quad \sigma_z^2 = \frac{1}{N'} \sum_{i=1}^{N'} (z_i - \langle z_i \rangle)^2 \quad [1]$$

$$234 \quad S_k = \frac{1}{N' \sigma_z^3} \sum_{i=1}^{N'} (z_i - \langle z_i \rangle)^3$$

235 where,  $z$  represents the bed elevation at location  $(x,y)$  in a DEM,  $N'$  is the total number of  
 236 DEM points and  $\langle \rangle$  represents the mean value.

237 Secondly, the inclination index ( $I_0$ ) in the flow direction was calculated using Equ. 2. Here,  
 238 the difference between the fraction of positive and negative slopes of particles, is divided by  
 239 the total number of positive, negative, and zero inclinations at a given lag (of 1 mm), which  
 240 is equal to the DEM resolution. A positive slope was counted as bed elevations increasing  
 241 downstream. A threshold value of  $\pm 0.01$  was set, so unreliable near-zero slopes were not  
 242 calculated in the numerator of Equ. 2 (Millane et al. 2006). Particle imbrication can be  
 243 inferred from positive inclination index values, which indicates a predominance of positive  
 244 slopes of the grains in the flow direction, reflecting the influence of downstream flow on the  
 245 bed surface (Laronne and Carson 1976; Millane et al. 2006).

$$246 \quad I_0 = \frac{n_+ - n_-}{N_s} \quad [2]$$

247 where,  $n_+$  and  $n_-$  are the number of positive and negative slopes between successive DEM  
 248 points, respectively, and  $N_s$  is the total number of slope measurements.

249 The slope and aspect of individual cells of the DEMs (Equ. 3) were analyzed, using a moving  
 250 window to calculate the elevations of surrounding cells, in order to provide information on  
 251 sediment textures, including any preferential grain imbrication and aspect orientation; this is  
 252 possible because the DEM cell size is smaller than the grain size (Hodge et al. 2009). Due  
 253 to the alignment of DEMs in the flow direction, those cells with  $90^\circ$  aspects indicate sloping  
 254 grains facing downstream and an aspect of  $270^\circ$  indicates sloping grains orientated  
 255 upstream. Further details of the calculation of these metrics are provided in the references  
 256 cited.

$$257 \quad S = \arctan \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}$$

$$258 \quad A = \arctan \left(\frac{dz}{dx} / \frac{dz}{dy}\right) \quad [3]$$

259 where  $\frac{dz}{dx}$  and  $\frac{dz}{dy}$  are the gradients in the center cell, determined from the elevations of  
 260 eight perimeter cells in both the x and y direction.

261 Finally, second-order structure functions (2DSF) were calculated (Equ. 4) to evaluate  
 262 changes in elevation correlations at differing lags and directions, which can provide an  
 263 indication to surface-forming mechanisms (Nikora et al. 1998; Aberle and Nikora 2006).  
 264 Gravel-bed structure functions can be separated into three regions: a scaling region with a  
 265 uniform slope at small lags, a saturation region at large lags with a slope of zero, and a  
 266 transition region between the two where the slope decreases (Nikora et al. 1998; Hodge et  
 267 al. 2009). Small values are indicative of areas of similar elevation, and hence the same grain  
 268 (as data is detrended to remove the influence of bedforms), and once values are saturated

269 they indicate that elevations are no longer correlated. Second-order structure functions are  
 270 displayed in 2D isopleth maps, which allow for the identification of the length and spatial  
 271 arrangement of surface layer features (Bertin et al. 2017), and horizontal roughness lengths  
 272 can be calculated in both the streamwise and cross-stream directions ( $L_x$  and  $L_y$ ). Horizontal  
 273 roughness lengths  $L_x$  and  $L_y$  are calculated from the breakpoint in the slope between the  
 274 scaling region and the saturation region of the 1D structure functions for  $\Delta x = 0$  and  $\Delta y = 0$ ,  
 275 respectively.

$$276 \quad D_{G2}(\Delta x, \Delta y) = \frac{1}{(N-n)(M-m)} \sum_{i=0}^{N-n} \sum_{j=0}^{M-m} \left\{ z(x_i + n\delta x, y_j + m\delta y) - z(x_i, y_j) \right\}^2 \quad [4]$$

277 where,  $\Delta x = n\delta x$  and  $\Delta y = m\delta y$ ;  $\delta x$  and  $\delta y$  are the sampling intervals (i.e. DEM resolution)  
 278 in the longitudinal and transverse directions respectively;  $n=1,2,3,\dots,N$  and  $m=1,2,3,\dots,M$ .  $N$   
 279 and  $M$  are the number of DEM points in the same two directions.

## 280 RESULTS

281 Roughness parameters were calculated with both distance down bar and distance from the  
 282 water edge (Fig. 4), in order to assess down bar and lateral variability in surface structure  
 283 and grain size.

284 Whereas there is no simple correlation of roughness parameters with distance down bar  
 285 and from the water edge (i.e., low  $R^2$  values and significant scatter in the data), there are  
 286 patterns of a reduction in surface sediment size (both  $d_{50}$  and  $d_{90}$  fractions of the surface)  
 287 with distance down bar, compared to an increase with distance from the water edge. There  
 288 is more scatter in data for  $d_{90}$  values due to the wider range in sediment size measured  
 289 across the patches (as seen in Table I, where values vary from 32 mm to 65 mm). Following  
 290 the pattern observed in sediment size, the standard deviation of elevations ( $\sigma_z$ ) decreases  
 291 with distance down bar and increases with distance from water edge. These patterns can

292 be seen qualitatively across patch surfaces, in particular a visible reduction in grain size at  
293 the downstream and water edge patches (Fig. 5).

294 In contrast to these patterns, skewness increases with both distance down bar and distance  
295 from the water edge. The majority of patches have positive skewness values, aside from  
296 P02 (bar head), which has a negative skewness ( $S_k = -0.0971$ ).

297 For both the inclination index and horizontal roughness lengths, the pattern follows that of  
298 sediment size and standard deviation of elevations, whereby each roughness parameter  
299 decreases down bar and increases with distance from the water edge. Therefore,  
300 consistencies in patterns of the roughness parameters are evident (Fig. 4), aside from  
301 skewness, which differs from the other roughness parameters.

302 Although there are these patterns in roughness parameters with distance down bar and from  
303 the water edge (Fig. 4), there is significant scatter in the data, largely due to the complex  
304 topography of the gravel surface. This scatter, and with low Pearson's coefficients of  
305 determination ( $R^2$ ) for the relations, is indicative of spatial variability in roughness statistics  
306 at the bar scale and reflects complex sedimentation patterns at this scale. The coefficients  
307 of determination for those roughness parameters for distance from the water edge are higher  
308 compared to those for distance down bar. This suggests a more robust relationship between  
309 distance and roughness statistics in a lateral direction, which has important implications for  
310 field data collection since such patterns are rarely explored.

311 Further results (Fig. 6) confirm a decrease in the median value of roughness parameters  
312 towards the bar tail for all parameters (e.g., sediment size,  $\sigma_z$ , inclination index and horizontal  
313 roughness lengths), except skewness, which displays an increase with distance down bar.  
314 There are also consistent decreases in the spread of data (variance in roughness statistics)  
315 towards the bar tail.

316 At the downstream end of the bar, median  $\sigma_z$  is 30% lower than the bar head values,  
317 consistent with fine grain sizes comprising the surface, as evident in the trends of reduced  
318  $d_{50}$ ,  $d_{90}$  and  $\sigma_z$  with distance down bar (Figs. 4 and 6). These patterns are in accordance  
319 with field results from the Fraser River, where a 33% reduction in median grain size from  
320 the bar head to the bar tail was documented (Rice and Church 2010). For our results, the  
321 mean values of the bar head and bar tail were compared using t-tests with a 95% confidence  
322 level, and were found to be statistically different for  $d_{50}$ ,  $\sigma_z$  and inclination index. There were  
323 significant differences between the bar center and the bar tail for all parameters, except  
324 skewness. All roughness parameters were found to be statistically similar between the bar  
325 head and bar center.

326 The surface slope and aspect are presented as polar plots for all patches and overlain on  
327 an enlarged schematic of the bar (Fig. 7). Flow is assumed to be from left to right in polar  
328 plots (i.e., from 270° to 90°). For all patches, the majority of aspects are upstream (around  
329 270°), particularly on patches upstream of the bar (including P01, P04, P05, P06, and P07).  
330 Patches P08 – P13 (bar center and bar tail) have a higher density of upstream aspects, but  
331 they also have more downstream aspects compared to those patches upstream. These  
332 observations of accentuated particle imbrication at the bar head compared to the bar tail  
333 follow previous results showing a reduction in inclination index at the bar tail (Fig. 6D).  
334 Further, the slopes of DEM cells (assumed to be grains) can be assessed. The highest  
335 slopes observed are about 80° (Fig. 7), and these are predominantly positioned  
336 perpendicular to the flow. Visually, this is shown by shaded areas going further away  
337 towards the circles' edges for 0° and 180° aspect angles (Fig. 7). This is more evident in  
338 patches P09 – P13 (bar center and bar tail) at the downstream end of the bar.

339 Examining the relationship between multiple roughness parameters and grain size provides  
340 a baseline for future studies. For our results, the strongest correlation exists between  
341 roughness lengths in the downstream direction ( $L_x$ ) and  $d_{90}$  (Fig. 8). Roughness parameters,

342 except skewness, and  $d_{90}$  have correlations ranging between  $R^2 = 0.47$  and  $0.88$ .  
343 Relationships between roughness parameters and  $d_{50}$  also display strong correlations ( $R^2 =$   
344  $0.71 - 0.85$ ) (Fig. 8). The exception, skewness, shows weak correlation ( $R^2 = 0.27$  and  $R^2$   
345  $= 0.21$  for  $d_{50}$  and  $d_{90}$  respectively). Even with the removal of the one anomalous site (P02,  
346 which has a negative skewness) the relationship is still below that of other roughness  
347 parameters ( $R^2 = 0.35$  and  $R^2 < 0.1$  for  $d_{50}$  and  $d_{90}$ , respectively).

## 348 **DISCUSSION**

### 349 *Assessing within-bar variability in surface roughness*

350 The assessment of  $\sigma_z$  is an improvement on the former technique of using grain size as a  
351 roughness parameter, as gravel beds with similar grain sizes can have contrasting  $\sigma_z$  values  
352 (Cooper and Tait 2009; Hodge et al. 2009). The pattern of higher  $\sigma_z$  values (i.e., indication  
353 of a rougher surface, Fig. 6B) upstream of the bar, at the bar head, and bar center, partly  
354 denotes coarser grains that have accumulated at these sites (Fig. 6A). Our observations of  
355 within-bar variability are attributed to varying locations and elevations on the bar. More  
356 specifically, field observations and an orthophoto (Fig. 3), indicate that upstream patches  
357 are elevated relative to the water line compared to patches at the bar tail, and may therefore  
358 be exposed for all but the highest flows, whereas patches at the bar tail are more frequently  
359 submerged. The pattern of upstream patches with larger sediment sizes and  $\sigma_z$  is  
360 comparable to patterns observed in laboratory studies, and is thought to reflect a coarse  
361 armor layer that formed as a result of higher discharges (Aberle and Nikora 2006).  
362 Contrasting roughness properties for patches at the bar tail may be due to exposure to more  
363 frequent sediment transport events and to submergence during lower flows. Differences in  
364 patch elevation on the bar also influence the distribution of bed shear stress during  
365 submergence, with higher bed shear stress occurring in areas on the bar top, due to higher  
366 velocities and reduced water depths. Previous experimental work showed an increase in



367 surface roughness with shear stress, which is relevant to this study (Aberle and Nikora  
368 2006). Further, data from Rice and Church (2010) showed that varying bar elevation  
369 determines shear stress distribution across the bar, which in turn determines the sediment  
370 size distribution.

371 Whereas the patches at the water edge are more frequently submerged by flows and contain  
372 smaller grain sizes, those patches nearer the bank of the river are more stable and have  
373 coarser sediment (Fig. 4, higher  $d_{50}$  and  $\sigma_z$ ). This suggests that these areas only experience  
374 high flow events (and are otherwise exposed), which winnow fine sediment and move the  
375 coarse sediment infrequently (Leopold and Wolman 1957). For the majority of patches on  
376 this bar, skewness values are positive, representing water-working across the bar, except  
377 patch P02 at the bar head (Fig. 4), which has a negative skewness value. This patch, located  
378 below the change in elevation (i.e., below the bar platform), near vegetation, could explain  
379 its singularity. The trend of increasing skewness with distance down bar is the opposite of  
380 other roughness parameters (Figs. 4 and 6), with the patches at the bar tail having higher  
381 skewness values, suggestive of fewer surface depressions from the deposition of fine  
382 sediment in any gaps between coarse sediment during subaqueous transport (Nikora et al.  
383 1998; Aberle and Nikora 2006).

384 All patches have positive inclination index values, indicating grain imbrication across the bar  
385 (Hodge et al. 2009; Qin and Ng 2012). This is consistent with the findings of Rice and Church  
386 (2010), who found that only two out of 87 of their locations displayed no evidence of  
387 imbrication. All of their locations were on primary and secondary unit bars, although the  
388 locations of the non-imbricated surfaces within the bars were not defined. Here, higher  
389 inclination index values at the bar head and near the bank (Figs. 4 and 6) suggest greater  
390 imbrication of particles and a higher degree of packing (Cooper and Tait 2009), and  
391 therefore sediment is more stable and less readily available for transport. Previous work has  
392 related grain imbrication to the movement of the coarse grains on the bed by rolling and

393 sliding (Laronne and Carson 1976), as those grains can stack against each other after  
394 meeting with an obstacle, forming imbricated grain structures. In contrast, the bar tail and  
395 the water edge have particles that may be more easily repositioned in future flow events due  
396 to the surface being poorly organized (Mao et al. 2011). Although inclination index values  
397 can provide information with regards to the imbrication of a surface, it is useful to combine  
398 this with the analysis of slope and aspect (Fig. 7), as this can determine the slope values of  
399 grains (Qin and Ng 2012).

400 Analysis of surface slope and aspect of DEM cells in polar plots (Fig. 7) has been used in  
401 only a few gravel-bed river studies to date (Hodge et al. 2009, Qin and Ng, 2012; Bertin and  
402 Friedrich 2016). Along with inclination index calculations, this method is more quantitative  
403 than previous assessments of imbrication in the field. Imbrication was previously assessed  
404 and categorized qualitatively, to extract information regarding the degree of reworking and  
405 mobility of grains, with 38% of locations classified as weakly imbricated and 60% of locations  
406 classified as strongly or very strongly imbricated (Rice and Church 2010). For all our patch  
407 locations (Fig. 7), there is a majority of upstream aspects (i.e., high density of points around  
408 270°), which is consistent with our previous observations of grain imbrication in a direction  
409 parallel to the flow using the inclination index (Hodge et al. 2009; Qin and Ng 2012). If  
410 imbrication is observed in a single direction, this can confirm the assumed flow direction  
411 from field observations (Bertin and Friedrich 2016), which in this study is true (Fig.7), where  
412 flow was assumed to be from 270 to 90°.

413 Our results quantitatively affirm previous geomorphological results. Although spatial  
414 variability within bars is of no surprise, as geomorphologists and sedimentologists frequently  
415 gather data from a consistent location (i.e., the bar head) when making inter-bar  
416 comparisons of surfaces (Rice and Church 2010), our study emphasizes that a single  
417 sample from one exposure cannot represent the whole gravel-bar surface. This has  
418 important implications for the development of a standardized sampling approach, and for

419 the selection of roughness parameters in models, which is difficult due to the displayed  
420 complexity (i.e., variability) of roughness at the bar-scale (Rice and Church 2010). Our  
421 empirical findings of variations in roughness across a gravel bar can be used to validate and  
422 calibrate flow resistance equations and morphodynamic models, including comparisons of  
423 model predictions with field data (Rice and Church 2010; Powell 2014).

#### 424 Examining roughness relationships with grain size

425 Throughout research, three roughness metrics are commonly used, as summarized in  
426 Pearson et al. (2017): (i) roughness height ( $rh$ ) (Vazquez-Tarrio et al. 2017), which is the  
427 difference in height between the top of the particle and the averaged topographic surface  
428 (i.e. mean-bed elevation); (ii) twice the standard deviation of elevations (Heritage and Milan  
429 2009); and (iii) root mean square height (RMSH), the standard deviation of heights in a given  
430 area for which the average slope has been detrended (Vazquez-Tarrio et al. 2017).

431 Pearson et al. (2017) summarizes published  $R^2$  values for grain size versus topographic  
432 elevation for fluvial systems only, and there is a range between 0.231 and 0.96, although  
433 50% of studies provide a strong relationship that exceeds  $R^2 = 0.8$ . Vazquez-Tarrio et al.  
434 (2017) found moderate to strong correlations for all roughness metrics ( $R^2 = 0.45 - 0.90$ )  
435 between surface roughness and truncated grain size (< 8 mm were removed). The best  
436 correlation was with  $rh$ -, and the weakest fit with RMSH.

437 To our knowledge, this is the first time the relationship between the studied roughness  
438 parameters (e.g., inclination index or horizontal roughness lengths) and grain size have  
439 been investigated (Fig. 8). The data on multiple roughness parameters and  $d_{50}$  in this study  
440 (Fig. 8) yield  $R^2$  values between 0.71 – 0.85, which lie in the range of published values  
441 (Pearson et al. 2017, Vazquez-Tarrio et al. 2017). The one exception is skewness, which  
442 has a weak correlation ( $R^2 = 0.27$ ) with grain size. Although skewness cannot be a proxy for  
443 grain size, it can contribute to the understanding of a surface (e.g. degree of water-working).

444 Case studies indicate that there are different relationships between surface roughness and  
445 grain size, reflecting different surface textural characteristics (Pearson et al. 2017; Vazquez-  
446 Tarrio et al. 2017). Further, patches with similarities in grain size have distinct roughness  
447 differences due to packing, burial and imbrication (Heritage and Milan 2009; Hodge et al.  
448 2009). There needs to be more data (including that of various roughness parameters) on  
449 differing sediment textures, to determine roughness and grain size relationships.

#### 450 *Inferring sedimentation patterns from roughness parameters*

451 The gravel bar studied in this paper is a channel side bar, or lateral bar, in a non-meandering  
452 section of the channel. Lateral channel bars attach to one bank, in a narrow section of the  
453 channel, and sediment accumulates at both ends of the bar (Church and Jones 1982).

454 Evidence of down bar decreases in sediment size,  $\sigma_z$ , and inclination index (Figs. 4 and 6)  
455 implies down bar fining in sediment. Bar heads are thought to have formed during high flows  
456 (Leopold and Wolman 1957; Bluck 1976), that transport coarser sediment that mantles the  
457 bed. Due to an inability of subsequent lower flows to transport the coarse sediment, it  
458 remains *in situ* (Leopold and Wolman 1957; Bluck 1976; Francalanci et al. 2012). The coarse  
459 sediment becomes the nucleus for bar development, by modifying local flow structures and  
460 creating local turbulence that leads to winnowing of fine sediment. Further, fine sediment is  
461 trapped at the margins of the bar and is moved downstream during a range of flow rates  
462 (Leopold and Wolman 1957; Parker 1975; Nanson 1980; Bluck 1982; Leopold 1992;  
463 Ashworth 1996).

464 From field observations, there is a well defined bar platform across the studied bar (Fig. 3)  
465 with dense vegetation (pampas grass) on top (Blacknell 1982). The junction between a  
466 channel and the bar platform is known as an avalanche face, and these can range between  
467 a few centimeters to a few meters high (Blacknell 1982, Rice et al. 2009). In the case of this  
468 bar, the avalanche face is approximately 1 meter high.

469 Due to the presence of a bar platform, the patches located at higher elevations (i.e., on the  
470 bar platform), and away from the water edge are strongly armored, with increased sediment  
471 size and  $\sigma_z$ . A tentative correlation between surface elevation (or bar thickness) and surface  
472 sediment size has previously been made, and this apparently contributes to deviations in  
473 reach-scale downstream fining trends (Rice and Church 2010). In comparison, those  
474 patches at the water edge appear to be undergoing multiple erosion and deposition cycles,  
475 and sediment accumulates there due to lateral accretion of fine grains (Bluck 1982) (Fig.  
476 9A). Downstream of the bar and bar platform, finer sediment is evident (reflected in a  
477 decrease in grain size and  $\sigma_z$  in Figs. 4 and 6). Along with lateral accretion, this could be  
478 due to the bar tail becoming a shadow zone during high flows (Fig. 9B). This depositional  
479 mechanism occurs as fine sediment is transported over the bar platform until subsequent  
480 falling flow stages result in the deposition of the sediment at the bar tail (Leopold and  
481 Wolman 1957; Burge 2006; Rice and Church 2010). The lateral accretion of sediment is  
482 substantiated by field observations of lighter colored sediment located below the bar  
483 platform near the water edge (e.g., P02), indicating it has been deposited more recently than  
484 the stable, darker sediment on the bar platform. Furthermore, increases in roughness  
485 parameters with distance from the water edge (Fig. 4), supports the idea that the bar is  
486 undergoing lateral accretion of sediment.

487 The scatter in our data (Fig. 4) suggests that the bar is complex in nature, with secondary  
488 sedimentation patterns, supporting observations made from historical images (Fig. 2) that  
489 demonstrate downstream propagation of the bar and provide evidence for cycles of erosion  
490 and deposition (Rice and Church 2010). Furthermore, sedimentation patterns on this bar  
491 may be difficult to interpret due to larger morphological features in the river channel at this  
492 location. Directly opposite this bar, is a rock revetment, which was installed *circa* late 2011  
493 (Hauraki Council Report 2011). In natural river channels, the deposition of sediment (e.g.,  
494 on exposed gravel bars) is compensated for by erosion of the opposite bank, in order for the

495 channel to maintain conveyance (Rice and Church 2010). However, in this case sediment  
496 deposition cannot be compensated for directly opposite the bar, which thus influences the  
497 flow and natural sedimentation patterns.

498 An improved understanding of the variability in bed roughness is beneficial for modeling  
499 purposes, and interpretations of sedimentation patterns and morphology. These are  
500 important for successful river restoration procedures and the management of natural  
501 systems. The Whakatiwai River studied has at times flooded local communities, and local  
502 people have called for effective management to be put in place to protect sacred cultural  
503 sites (Hauraki Council 2011). Therefore, developing and improving the understanding of  
504 sedimentation patterns can guide management strategies in the future, which is applicable  
505 to other locations around the globe.

506 Further, roughness properties can be measured between flow events to provide a signature  
507 of erosional and depositional processes (Smith, 2014). Previous research has not  
508 established a direct association between changes in grain size and morphological change  
509 (Rice and Church 2010; Vazquez-Tarrio et al. 2017). However, we suggest that applying the  
510 technique presented in this manuscript multiple times (i.e., following flow events), can aid in  
511 the detection of temporal changes in roughness and help to relate changes in roughness to  
512 morphological changes. This could involve the installation of GPS markers in order to  
513 identify where the patch locations were for repeat surveys.

## 514 **CONCLUSION**

515 This study investigated intra-bar variability in roughness statistics across a bar at 14 patch  
516 locations extending 35 m down bar and 5 m across the bar from the water edge. This  
517 extends previous work that focused on grain size and qualitative estimates of parameters  
518 such as imbrication. Data were collected using close-range photogrammetry, a technology  
519 used for the first time to assess intra-bar variations of surface roughness.

520 Roughness statistics were found to vary across the bar, with evidence of down bar  
521 reductions in grain size, changes in standard deviation of elevations, imbrication of particles,  
522 variations in horizontal roughness lengths, and an increase in skewness down bar. This  
523 paper therefore provides quantification of earlier observations of sorting across a bar. There  
524 is a stronger correlation of increased roughness with distance from the water edge. This  
525 lateral variation of roughness and sedimentation patterns across gravel bars is infrequently  
526 documented, compared to down bar patterns, but is an important consideration for a wide  
527 range of fluvial studies, including river restoration. It is also important for choosing a location  
528 in the field to measure roughness properties. Relationships between roughness parameters  
529 and grain size ( $d_{50}$ ) were examined and strong correlations ( $R^2 = 0.71 - 0.85$ ) were found in  
530 all parameters except skewness. Assessing the relationship between roughness parameters  
531 and grain size is timely, as previously no universal relationship has been found, suggesting  
532 grain size cannot be used as a proxy for surface roughness.

533 Following on previous photogrammetry and laser-scanning studies, this study infers  
534 sedimentation patterns from roughness statistics, with the consideration of wider  
535 morphological influences. The trends observed in this study are indications of sediment  
536 deposition at the bar tail and water edge, and coarse stable sediment at the bar head and  
537 near the banks of the bar; which are consistent with lateral accretion. Inferring sedimentation  
538 patterns from these roughness statistics can be difficult due to scatter in the data,  
539 highlighting the complexity of surface roughness, which result from several cycles of erosion  
540 and deposition. Understanding these sedimentation patterns in the Whakatiwai River, and  
541 other rivers, is needed for the successful implementation and monitoring of river  
542 management.

543 This paper has highlighted the variability in roughness statistics across a gravel bar and the  
544 benefit of using a range of surface metrics to corroborate observations. Future work that  
545 would benefit geomorphologists, includes the assessment of roughness parameters at a

546 larger scale (i.e., to include the effect of bedforms), quantification of roughness parameters  
547 on multiple bars in different river systems, assessments of roughness over temporal scales,  
548 and identifying if a single roughness parameter can be used to represent larger-scale  
549 roughness. This would assist in the development of flow resistance, morphodynamic and  
550 empirical models.

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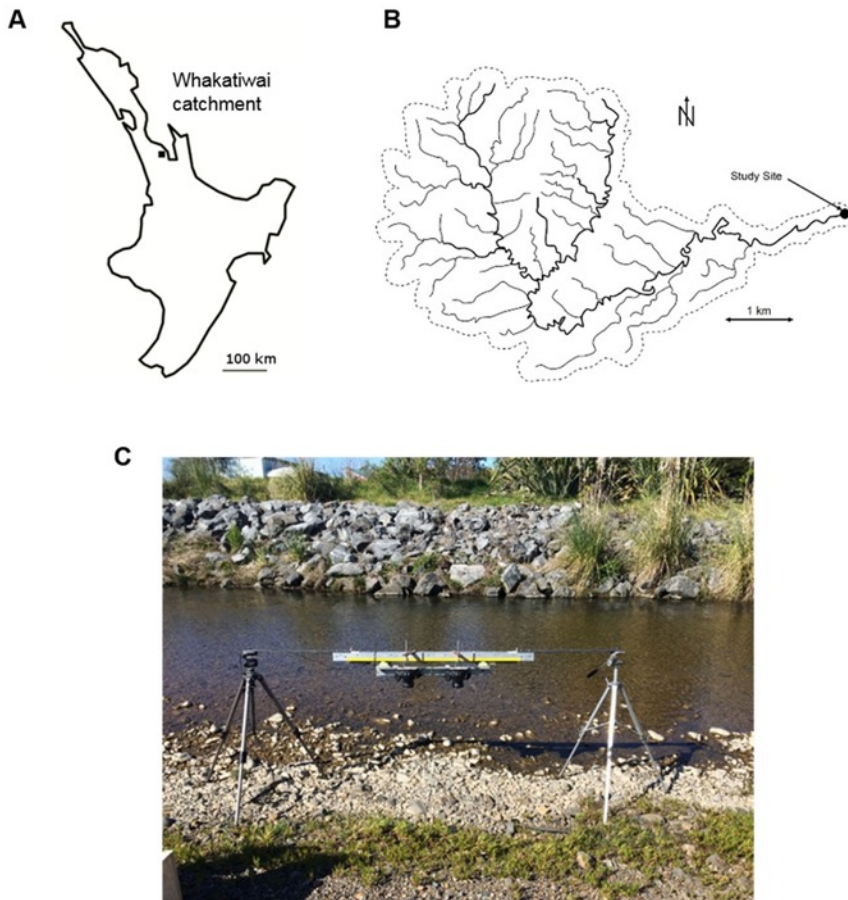
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- 721

722 **FIGURE CAPTIONS**

723

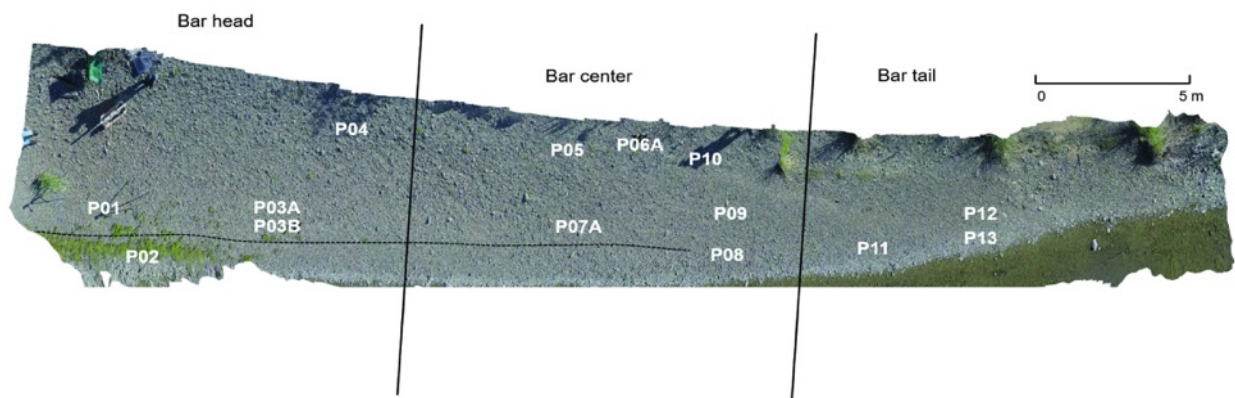
724 **Figure 1.** Whakatiwai catchment, located in the north east of North Island, NZ (a), with study  
725 site located near the stream mouth (b). Photo of close-range photogrammetry setup of  
726 patches, with a rock revetment visible on the opposite bank of the stream (c).





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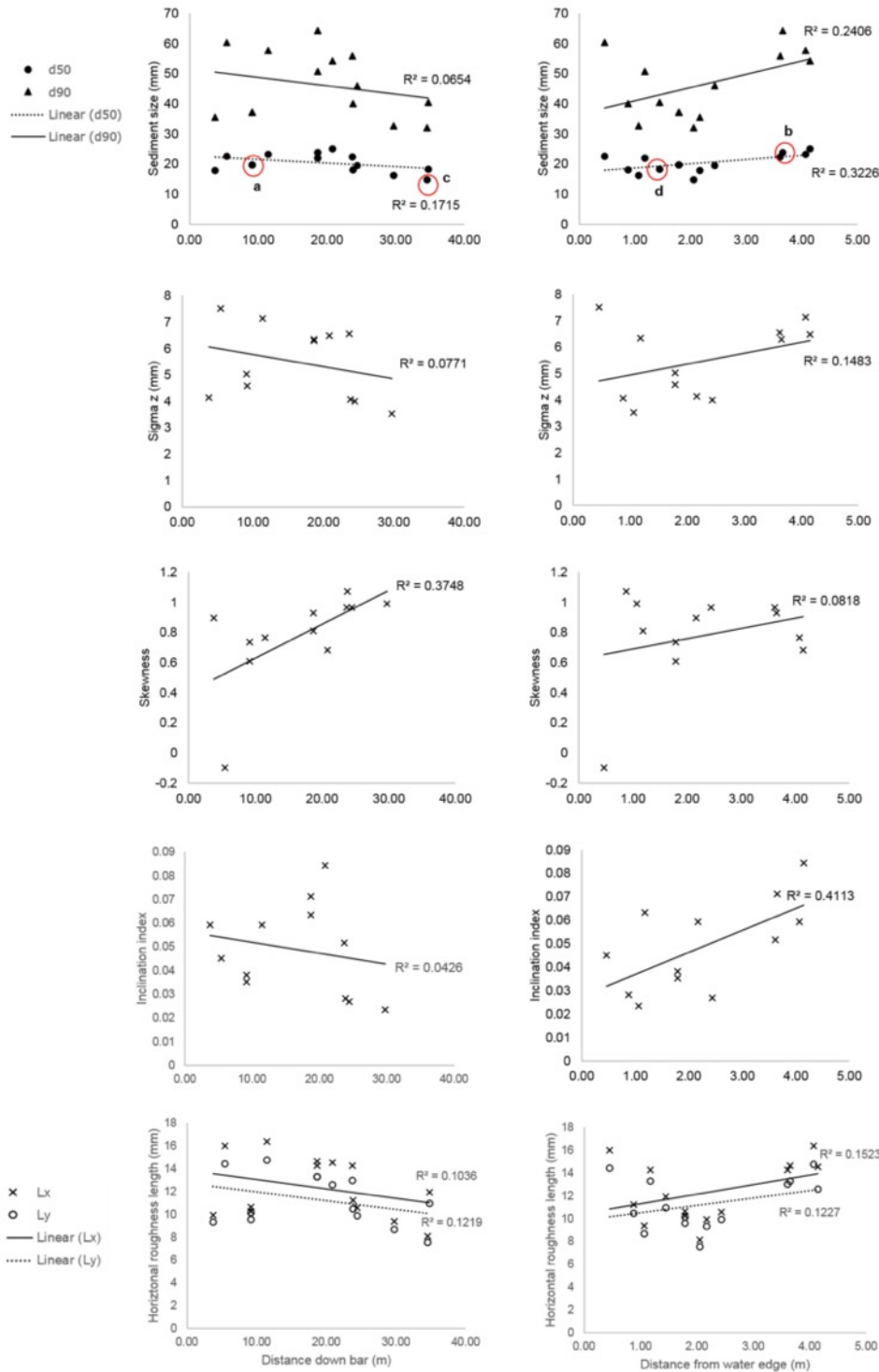
728 **Figure 2.** Images showing the evolution of the bar under investigation from 2015 (A), 2013  
 729 (B), 2010 (C) and 2003 (D). The gravel bar is highlighted by dashed black lines, and flow  
 730 direction is shown by the block black arrow (in 2a), left-to-right of images. These images  
 731 provide context for the bar, surrounded by farmland and densely vegetated banks. In the  
 732 2013 and 2015 images (top row), the addition of the rock revetment can be seen on the  
 733 opposite bank from the bar. Source: Google Earth.



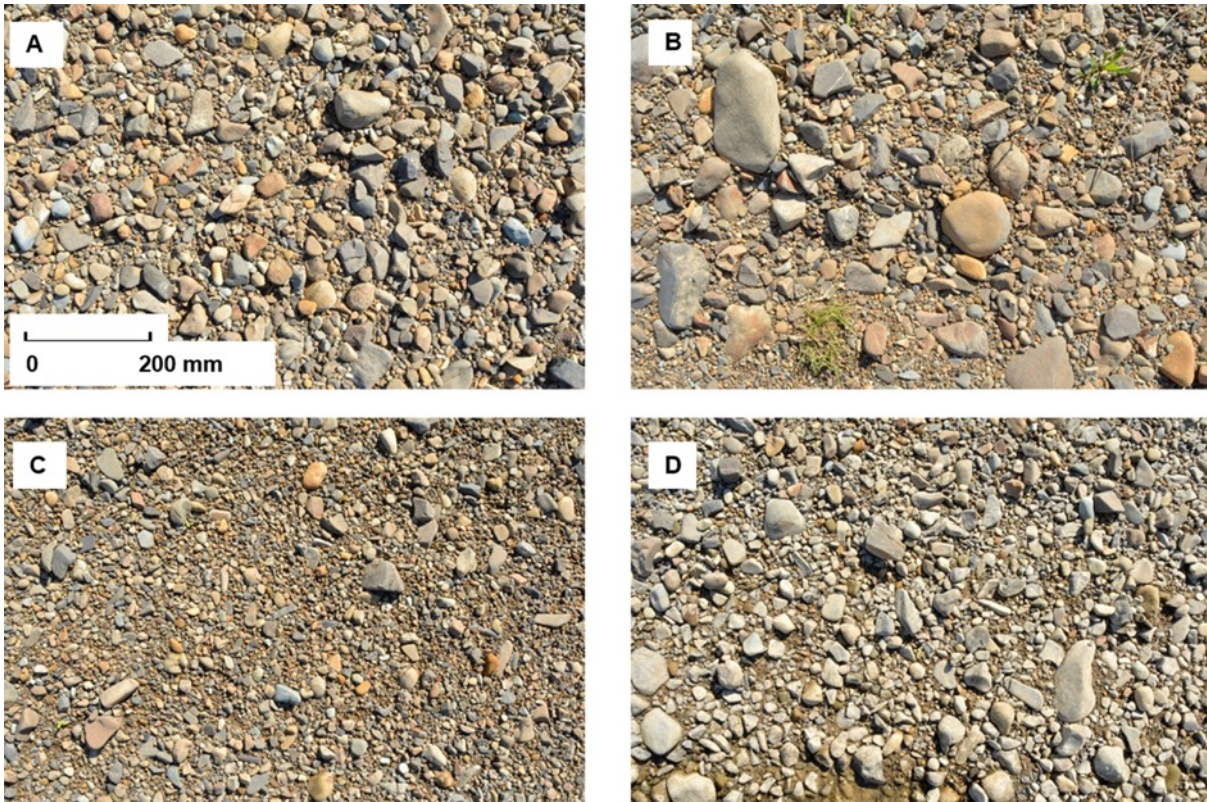
734

735 **Figure 3.** Schematic of gravel bar, overlaying an orthophoto of the bar, indicating the  
 736 location of 14 measurement patches, moving down a 30 m transect downstream, and across

737 bar. Black dotted line represents a break in slope and vegetation is represented  
 738 schematically across the bar.

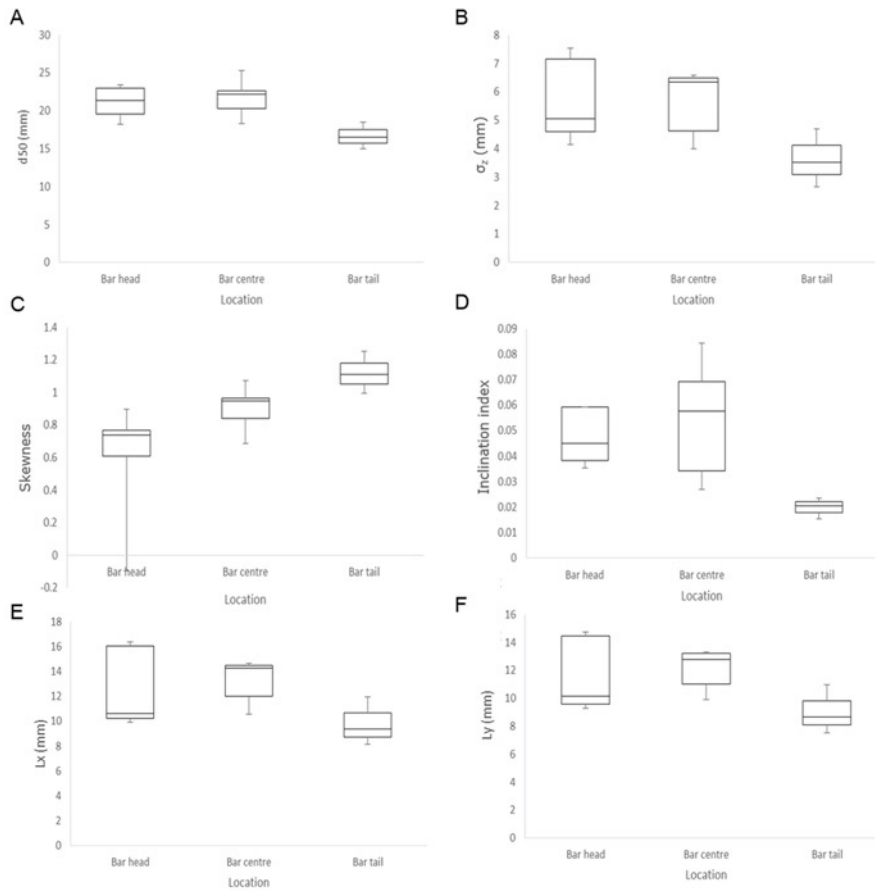


739  
 740 **Figure 4.** Roughness statistics (including sediment size, standard deviation of elevations,  
 741 skewness, inclination index and horizontal roughness lengths) with distance down bar and  
 742 distance from the water edge for all 14 patches measured. Circled data points in the top  
 743 graphs and associated labels refer to figure labels in Figure 5.



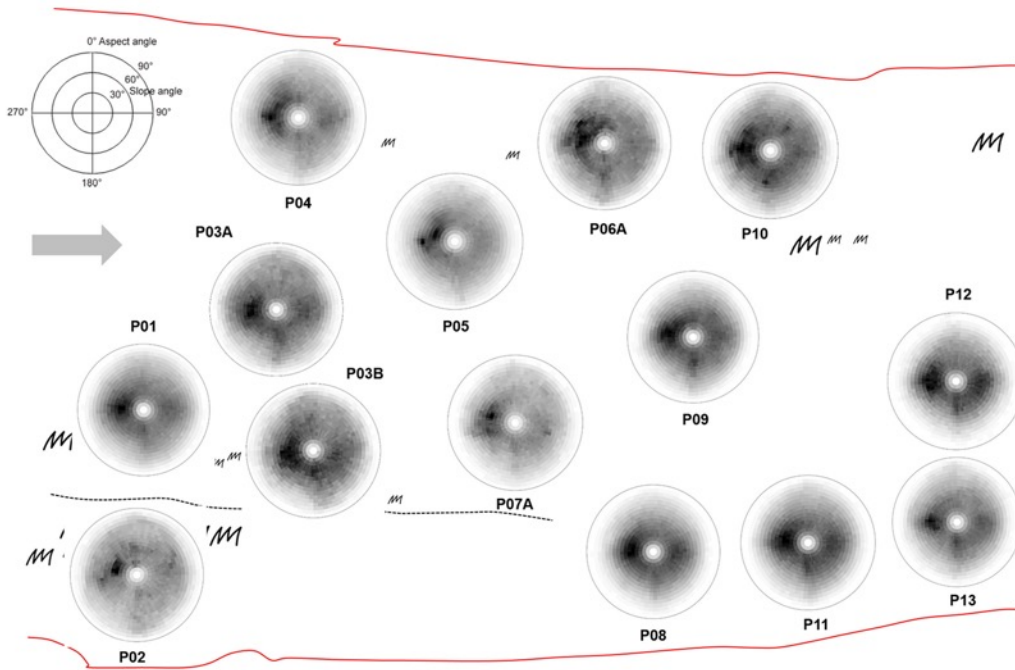
744

745 **Figure 5.** Photographs of grain size at upstream patch P03A (a), away from the water edge  
746 P05 (b), downstream P12 (c) and at the water edge P13 (d). All photographs are the same  
747 size and taken from the same height above the bed. The grain size data for these patches  
748 are circled and labelled in Figure 4.



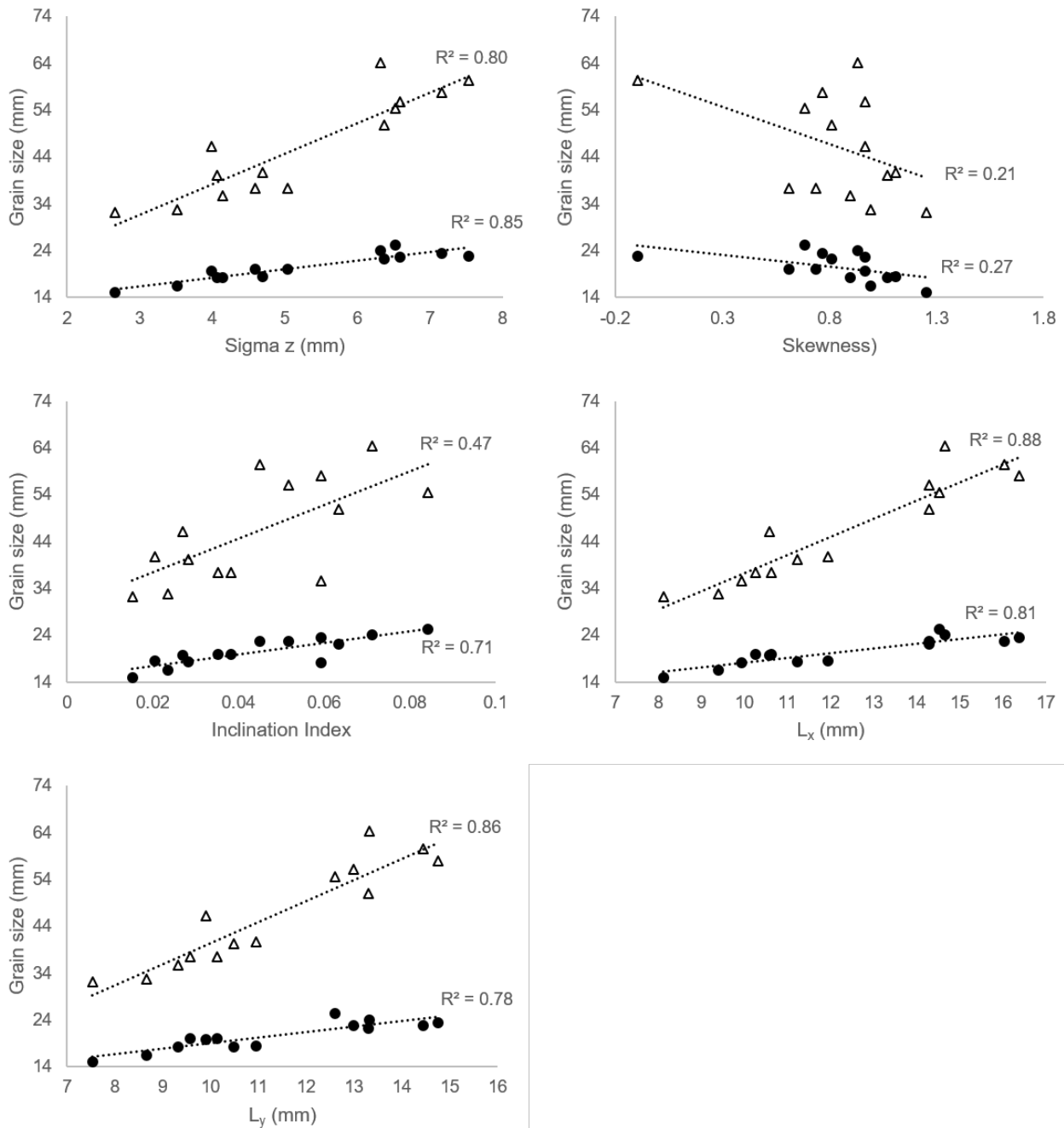
749

750 **Figure 6.** Boxplots of roughness statistics; (a)  $d_{50}$ , (b)  $\sigma_z$ , (c) skewness, (d) inclination index,  
 751 (e) horizontal roughness length  $L_x$  and (f) horizontal roughness length  $L_y$ , for three locations  
 752 of the bar (sample size  $n = 5$  for bar head,  $n = 6$  for bar center and  $n = 3$  for bar tail). The  
 753 horizontal line in the boxplot represents the median value for each location, the upper and  
 754 lower box limits represent the 75 % and 25 % percentiles respectively and whiskers display  
 755 the range in values.



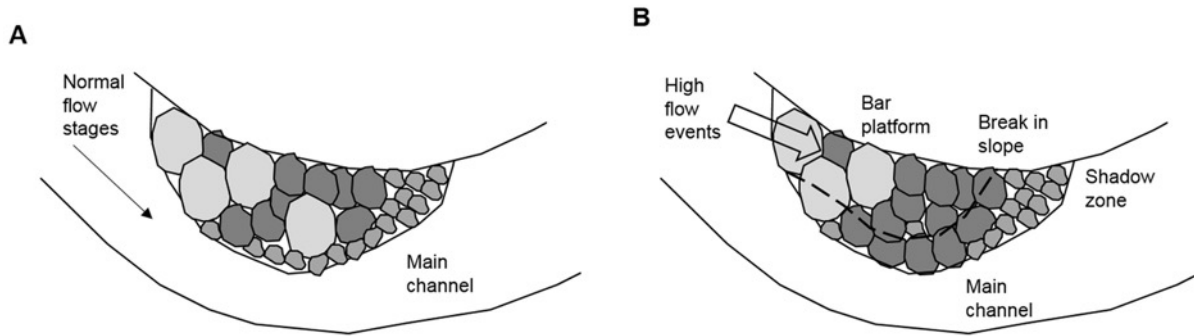
756

757 **Figure 7.** Surface slope and aspect polar plots, presented on an enlarged schematic of the  
 758 bar (as per Figure 3) to enable location of patch to be identified. Flow is assumed from left  
 759 to right (grey arrow). Aspect angle is from 0 to 360° and slope angle is from 0 to 90°, with  
 760 high density of points shaded black, and low density of points shaded white. Black dotted  
 761 line represents a break in slope and vegetation is represented schematically. Note that the  
 762 placement of polar plots is not to scale.



763

764 **Figure 8.** Roughness relationships for standard deviation of elevations, skewness,  
 765 inclination index and horizontal roughness lengths with grain size. Circles represent  $d_{50}$  grain  
 766 size and open triangles represent the  $d_{90}$  grain size.



767

768 **Figure 9.** Schematic of sedimentation patterns occurring on this bar. (a) Lateral accretion,  
 769 whereby fine sediment is deposited at the edge of the bar and downstream. (b) Down bar  
 770 fining due to sediment being transported over the bar platform during high flows and  
 771 deposited in the shadow zone during the falling limbs of hydrographs.