Moving-Window Detrending for Grain-Roughness Parameterization

Jane Groom, Stéphane Bertin, Heide Friedrich

► To cite this version:

Jane Groom, Stéphane Bertin, Heide Friedrich. Moving-Window Detrending for Grain-Roughness Parameterization. Journal of Hydraulic Engineering, 2019, 145, 10.1061/(asce)hy.1943-7900.0001612 . hal-03470794

HAL Id: hal-03470794

<https://hal.science/hal-03470794>

Submitted on 21 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

On the need for moving-window detrending for grain-roughness parameterisation

Jane Groom (jgro800@aucklanduni.ac.nz)¹,

Ph.D. Student, Department of Civil and Environmental Engineering, University of Auckland,
Private Bag 92019, Auckland 1142, New Zealand.

Stephane Bertin (s.bertin@ymail.com),

Postdoctoral Researcher, Department of Civil and Environmental Engineering, University of
Auckland, Private Bag 92019, Auckland 1142, New Zealand.

Heide Friedrich (h.friedrich@auckland.ac.nz)

Senior Lecturer, Department of Civil and Environmental Engineering, University of Auckland,
Private Bag 92019, Auckland 1142, New Zealand.

¹Corresponding author

Abstract

Detrending is required to remove large topographic trends from fluvial data, to enable robust parameterisation of surface roughness. A range of detrending methods exist in the literature, however there is limited presentation of the effect of these methods on output roughness statistics. Here, the results of non-detrended data are presented compared to flat-surface detrending (e.g. removal of bed slope and setup misalignment) and moving-window detrending (e.g. removal of non-linear bed undulations) on a wide suite of roughness statistics. Digital Elevation Models (DEMs) of gravel surfaces obtained from the field and the laboratory are

analysed. Roughness statistics include the coefficient of variation of the standard deviation of elevations, standard deviation of elevations, skewness, kurtosis, inclination index and horizontal roughness lengths from second-order structure functions. Similarities exist between non-detrended data and the data detrended using flat-surface detrending. The moving-window detrending method results in lower roughness statistics in the coefficient of variation, standard deviation of elevations and horizontal roughness lengths. In contrast, higher values of skewness and kurtosis are observed with the moving-window detrending method. These differences in roughness statistics with the detrending methods support the use of a moving-window detrending method for robust grain-roughness parameterisation, through the removal of larger topographic signatures and roughness scales (e.g. the influence of bedforms). Furthermore, we highlight that comparisons between grain-roughness studies need to ensure the same procedure of detrending has been applied.

Introduction

The ease of collecting high-resolution topographic data has facilitated the accurate quantification of bed topography in a multitude of geomorphic applications. In fluvial research, roughness parameterisation is increasingly under investigation due to the dynamic interactions between sediment and flow (Aberle and Nikora 2006, Baewert et al. 2014, Hodge et al. 2009a), and the need for quantitative inputs for flow resistance equations and hydraulic models (Aberle and Smart 2003, Tuijnder and Ribberink 2012). Accurate parameterisation is required to avoid errors in modelling (Lane 2005, Morvan et al. 2008). Amongst this, guidance on how to work with these topographic datasets is needed in order to provide coherence in research, including recommendations on analytical procedures such as detrending methods.

Surface detrending is common practice in topographic surveys, as this removes larger scale trends that would otherwise conceal the scale of interest (Hodge et al. 2009a, Smart et al. 2002).

Grain-roughness parameterisation often removes large-scale topography, including the influence of bed slope or bedforms (Bertin and Friedrich 2014, Curran and Waters 2014, Hodge et al. 2009a, Smart et al. 2004). However, there needs to be a compromise between the trends removed from the surface and the loss of key topographic information contributing towards the surface roughness (Aberle and Nikora 2006, Hodge et al. 2009a, James et al. 2007).

Soil roughness studies have identified that roughness properties are sensitive to the detrending method used, and the measured roughness scale (Verhoest et al., 2008; Diaz et al., 2010). Gravel-bed roughness studies have used a range of methods for detrending, including; linear trends in both the cross stream and downstream direction (Cooper and Tait 2009, Curran and Waters 2014); a second-order biquadratic filter (Bertin and Friedrich, 2014); and a moving filter which removes a higher degree polynomial trend (Bertin et al. 2017, Powell et al. 2016, Smart et al. 2002). Besides, a moving filter controls the scale of the trend being removed from the surface, which enables the isolation of differing scales of roughness, including bedform or grain roughness (Bertin et al., 2017). A summary of the detrending methods used in relevant studies for gravel-bed roughness characterisation is presented in Table 1.

These variations in detrending methods used in research demonstrate a need for an investigation into the effect of detrending on roughness statistics, to enable a consistent output of roughness parameters comparable between studies (Bertin et al., 2017), and to provide recommendations on the required detrending method specific to the research (Diaz et al., 2010). The aim of this technical note is to build upon existing analysis, and investigate the effect of detrending methods on a wider range of roughness parameters.

Methodology

With the objective of this note being the assessment of detrending procedures, previously published data is used (Bertin et al. 2017, Groom et al. 2018b), with a concise overview of the

data collection process and methodology presented below, with further details presented in previous papers.

Data collection

Five DEMs are analysed (three from a field environment and two from the laboratory). Field DEMs were collected from the bar head of exposed gravel bars in the Whakatiwai Stream, New Zealand (Bertin and Friedrich (2016)). Laboratory DEMs were collected from armoured beds generated in the flume, at a constant flow rate of 84 L/s and a water depth of 0.225 m, under sediment starvation conditions. Differences in the two lab surfaces result from the sediment mixtures (15% sand and 85% gravel, and 9% sand and 91% gravel, respectively). All five surfaces are presented in recent work, where our Lab 1 and Lab 2 refer to the surfaces Sed1_Q2 and Sed2_Q2 (Table 1 in Bertin et al. (2017)) and field surfaces reflect the same naming structure. Further details of the surfaces, including DEM size and grain size information can be found in the Bertin et al. (2017). Surface grain sizes were determined using Basegrain®, which automatically detects the intermediate grain axis from a single vertical photograph (Detert and Weitbrecht 2012). To define the surface sediment (separate from the bulk sediment), we use the subscript ‘A’.

All DEMs were obtained by the photogrammetric technique using a pair of Nikon D5100 cameras with Nikkor 20 mm lenses installed in stereo vertically above the gravel. Cameras were calibrated (Zhang 2000) and images were rectified (maximum error < 1 mm), before using a stereo-matching algorithm (Gimel'farb 2002) to generate point cloud data. Point clouds were subsequently interpolated onto a regular grid (1 mm spacing) to obtain DEMs, which underwent quality testing, including the replacement of outliers using bi-cubic spline interpolation (less than 1 % of DEM points) and normalising the DEMs (by subtracting the mean value) to have a mean bed level equal to zero. All DEM resolution and vertical errors

(0.36 – 0.59 mm) were small compared to the sediment size, which is a precondition for suitable grain-roughness characterisation (Hodge et al. 2009b).

Detrending methods

To simultaneously determine any bed slope and setup misalignment (Bertin and Friedrich, 2014), commonly a least-squares flat surface is fitted to the raw DEMs (Eq. 1) (e.g., Aberle and Nikora, 2006; Bertin and Friedrich, 2016). In other literature this is known as bi-linear detrending (i.e. linear detrending in both the streamwise and transverse directions), however we refer to this method as flat-surface detrending from herein:

$$z_{trend} = a_0 + a_1x + a_2y \quad [1]$$

where a_i are constants, while x and y are the horizontal coordinates (parallel and perpendicular to the flow direction, respectively) and z is elevation.

Secondly, a moving-window detrending strategy (Smart et al., 2002; Powell et al., 2016; Bertin et al., 2017) was used and aimed at removing large scale distortions of the bed surface (i.e., bedforms), such as hollows and humps larger than typical cluster size. Following the method of Smart et al. (2002), the trend surface was estimated over a grid with point spacing $1.25 \times D_{90A}$, with the elevation of grid points measured by averaging DEM data points within a circle of diameter $2.5 \times D_{90A}$ centred on the grid point. Bi-cubic spline interpolation was used to interpolate between trend surface grid points and the location of the original DEM data points. The reader can refer to Figure 1 in Bertin et al (2017) for an example of the differences between the detrended DEMs.

Calculation of roughness parameters

Using the raw DEMs (i.e., non-detrended), and following the application of both detrending methods, surface metrics are calculated to obtain roughness parameters. Bed elevation

moments including the standard deviation of elevations (i.e. vertical roughness) (Aberle and Nikora 2006, Noss and Lorke 2016), skewness (indication of water-working) (Aberle and Nikora 2006) and kurtosis (measure of uniformity) (Coleman et al. 2011) are calculated. Further, the inclination index is calculated to assess the imbrication of particles (Millane et al. 2006, Smart et al. 2004) and the horizontal roughness lengths (L_x and L_y) from second-order structure functions are calculated to quantify the correlations of bed elevation in different directions (Nikora et al. 1998).

In order to assess the spatial variations in roughness parameters, a moving-window approach was undertaken whereby the metrics were calculated for increasing moving-window sizes across the DEM (see Groom et al 2018b for more details). Each window size was normalised by the D_{50A} (i.e. median grain size of the surface sediment) in order to facilitate comparisons between surfaces studied. For a given window size, the window was moved across the DEM, with an overlap of 95% between successive windows to ensure adequate calculation of roughness statistics (Groom et al. 2018b). Finally, the coefficient of variation (CV) of the standard deviation of elevations (calculated as the standard deviation of this parameter determined over all moving windows, divided by the mean and expressed as a percentage) is calculated to provide information regarding the spatial variability across a surface.

Results

Coefficient of variation of the standard deviation of elevations (CV) reduces with increased moving-window size for all three detrending methods, with similarities between non-detrended data and flat-surface detrending (Fig. 1). Moving-window detrending data has lower CV values compared to the other methods up to moving-window sizes of $(10 \times D_{50A})^2$, except for Field 2. Both the similarities in roughness properties between non-detrended and flat-surface

141 detrending, and lower values in moving-window detrending, are repeated when calculating the
142 standard deviation of elevations (Fig. 2).

143 Similarities exist for all detrending methods in skewness and kurtosis (in Field 1, 3 and Lab 2);
144 however, at larger moving-window sizes the moving-window detrending method demonstrate
145 higher values (Figs. 3 & 4). All patches display positive median skewness values, regardless
146 of detrending.

147 Due to the scale of Figure 5, for inclination index (*IO*), visually it appears there are limited
148 differences between all detrending methods. However, a detailed examination evidences
149 differences in *IO* between detrending methods close to 20 %, which is in accordance with the
150 differences observed for the other parameters. Nevertheless, all patches have positive median
151 inclination index values.

152 Horizontal roughness values (both L_x and L_y) are significantly lower for moving-window
153 detrending (Figs. 6 & 7). There are similarities between non-detrended data and flat-surface
154 detrending for the majority of patches, but Field 1 and Field 2 have the highest values in the
155 non-detrended data (Figs. 6 & 7).

156 To summarise, there are lower statistics for the data detrended with the moving-window
157 detrending in CV of the standard deviation of elevations (except Field 2), standard deviation
158 of elevations and horizontal roughness lengths (Figs. 1, 2, 6 & 7). In contrast, there are higher
159 values for skewness and kurtosis (Figs. 3 & 4) for moving-window detrending. For the majority
160 of patches, there are similarities in the non-detrended data and flat-surface detrending for each
161 roughness parameter.

162 Another important observation are the observed decreases in the variability in roughness
163 statistics with increases in moving-window size, until a plateau is reached. Plateaus are

displayed with a horizontal black line. This indicates that a sufficient DEM size is needed in order to obtain roughness statistics representative of the surface (Bertin et al. 2017, Groom et al. 2018b). In the CV graphs, particularly for the Field DEMs (Fig. 1), there are plateaus in the data using flat-surface detrending, followed by a further decrease in CV at larger window sizes (e.g. at $(20 \times D_{50A})^2$ in Field 1 and Field 3). This is attributed to two scales of roughness present across the surface, and provides evidence for the surface heterogeneity evident in natural systems (Graham et al. 2010, Nelson et al. 2014). As this is touched upon in previous work (Groom et al. 2018b), we limit our discussion of these observations and instead focus on the implications of the results displaying the effect of detrending.

Discussion

Using a moving-window detrending method extracts differing roughness statistics compared to using other detrending methods (for all parameters), supporting both evidence of a sensitivity to the method of detrending in previous applications and the existence of multiple scales of roughness (Bertin et al. 2017, Diaz et al. 2010, Robert 1990). Moving-window detrending provides lower roughness statistics for multiple parameters (except skewness and kurtosis) due to the detection of grains only, as a result of the bedform removal (Smart et al., 2002; Bertin et al., 2017). For the case of horizontal roughness lengths (Figs. 6 & 7), rather than similarities between the non-detrended and flat-surface detrended data, the non-detrended method has higher values (in Field 1 and 2). The importance of removing trends from the data before calculating second-order structure functions has previously been highlighted in research (Goring et al. 1999). Here, as a result of the non-detrended data lacking first-order stationarity, the predictions of horizontal roughness lengths are deemed to be inaccurate and meaningless for grain-roughness parameterisation.

Certain roughness parameters attain stable median values (i.e. plateau) at smaller window sizes than in the case of flat-surface detrending, and with lesser variability. In Bertin et al. (2017), this was related to moving-window detrending removing the effect of bedforms and measuring grain roughness only, as in this case, topographic irregularity and roughness relate solely to surface-grain characteristics. In contrast, DEMs detrended with a flat-surface also incorporate surface roughness due to bedforms, which occur at a larger spatial scale than grain roughness, and therefore require larger DEM sizes to obtain representative roughness parameters (Powell et al., 2016; Bertin et al., 2017, Groom et al. 2018b).

Throughout a majority of previous studies (Table 1), detrending is briefly mentioned as a necessary step in the process of DEM analysis. However, rarely is the significance of this step in the analysis stated, and some studies fail to mention the method of detrending (i.e., removing a linear trend or more complex trends), as shown in Table 1. Our work demonstrates that the method of detrending influences not only the output statistics, but also the roughness scale of interest (e.g. grain roughness or bedform roughness). Therefore, for an effective detrending method, the scale of investigation must be considered prior to analysis, in order to remove an appropriate trend, as shown in this study and previous studies on gravel patches (Bertin et al. 2017, Hodge et al. 2009a, Nestler and Sutton 2000). Comparisons of roughness between studies need to ensure the same procedure of detrending has been followed, in that the same trend has been removed, in order for the same roughness scale (e.g., grain roughness) to be considered (Qin and Ng 2012, Trevisani and Cavalli 2016).

Finally, although this technical note presents the need to remove large topographic trends for grain-roughness parameterisation, it is essential that for certain applications, such as linking flow processes to topography, meaningful trends of significance are not removed (Smith, 2014). For example, local flow properties are influenced by the turbulence generated by the

clusters observed in patches (e.g., Robert et al. (1996)), but also by topography which is outside of the measurement window (e.g., Lamarre and Roy, 2005; Legleiter et al., 2007). Therefore, if the influence of larger trends and the effect of clusters are removed, vital aspects of the topography that interact with the flow are subsequently removed. It must be considered what the resultant roughness statistics are aiming to represent, whether that be capturing the topographic detail or in use for explaining the interactions at the sediment-water interface in rivers. Our work provides insights into the relevance of detrending in analysis, but also in providing useful information regarding the surface. This avenue of research has been recently investigated, with results from a large number of surfaces presented in Bertin et al., (2017). Together, these studies show the importance of consistent analytical methods for gravel-bed DEMs, enabling comparisons of roughness measured between studies, and to further advances, not only in parameterising roughness from the bed topography, but understanding how the bed roughness can influence local flow properties.

Conclusion

Building on existing research demonstrating the importance of characterising the multiple scales of roughness across a gravel patch, this work presents the effect of detrending on roughness parameters. Across both field environments and laboratory surfaces, there are similarities between the non-detrended data and the data detrended using the flat-surface method. Throughout a suite of roughness statistics (including CV, standard deviation of elevations and horizontal roughness lengths), those values detrended using the moving-window method have lower statistics than using the other methods. In contrast, there are higher values in the moving-window detrended data compared to the other methods, for roughness statistics including skewness and kurtosis. Our assessment shows that using moving-window detrending provides the optimal results for grain-roughness studies, due to the removal of the bedform

roughness, enabling accurate characterisation of grain structure across a surface. Therefore it is important to determine the scale of interest prior to analysis, and comparisons between research require consistency in detrending methods, in order to adequately compare the same scale of roughness.

Acknowledgements

The study was partly funded by the Marsden Fund (Grant No. UOA1412), administered by the Royal Society of New Zealand.

References

Aberle, J. and Nikora, V. (2006) Statistical properties of armored gravel bed surfaces. *Water Resources Research* 42(11), W11414.

Aberle, J., Nikora, V., Henning, M., Ettmer, B. and Hentschel, B. (2010) Statistical characterization of bed roughness due to bed forms: A field study in the Elbe River at Aken, Germany. *Water Resources Research* 46(3), W03521.

Aberle, J. and Smart, G.M. (2003) The influence of roughness structure on flow resistance on steep slopes. *Journal of Hydraulic Research* 41(3), 259-269.

Baewert, H., Bimböse, M., Bryk, A., Rascher, E., Schmidt, K.-H. and Morche, D. (2014) Roughness determination of coarse grained alpine river bed surfaces using Terrestrial Laser Scanning data. *Zeitschrift für Geomorphologie, Supplementary Issues* 58(1), 81-95.

Bertin, S. and Friedrich, H. (2014) Measurement of gravel-bed topography: evaluation study applying statistical roughness analysis. *Journal of Hydraulic Engineering* 140(3), 269-279.

Bertin, S. and Friedrich, H. (2016) Field application of close-range digital photogrammetry (CRDP) for grain-scale fluvial morphology studies. *Earth Surface Processes and Landforms* 41, 1358 - 1369.

258 Bertin, S. and Friedrich, H. (2018) Effect of surface texture and structure on the development
 259 of stable fluvial armors. *Geomorphology* 306, 64-79.

260 Bertin, S., Friedrich, H., Delmas, P. and Chan, E. (2013) The use of close-range digital stereo-
 261 photogrammetry to measure gravel-bed topography in a laboratory environment.

262 Bertin, S., Groom, J. and Friedrich, H. (2017) Isolating roughness scales of gravel-bed patches.
 263 *Water Resources Research* 53, 6841 - 6856.

264 Brasington, J., Vericat, D. and Rychkov, I. (2012) Modeling river bed morphology, roughness,
 265 and surface sedimentology using high resolution terrestrial laser scanning. *Water Resources*
 266 *Research* 48(11), 1 - 18.

267 Butler, J.B., Lane, S.N. and Chandler, J.H. (2001) Characterization of the structure of river-
 268 bed gravels using two-dimensional fractal analysis. *Mathematical Geology* 33(3), 301-330.

269 Coleman, S.E., Nikora, V.I. and Aberle, J. (2011) Interpretation of alluvial beds through bed-
 270 elevation distribution moments. *Water Resources Research* 47(11), W11505.

271 Cooper, J.R. and Tait, S.J. (2009) Water-worked gravel beds in laboratory flumes—a natural
 272 analogue? *Earth Surface Processes and Landforms* 34(3), 384-397.

273 Curran, J.C. and Waters, K.A. (2014) The importance of bed sediment sand content for the
 274 structure of a static armor layer in a gravel bed river. *Journal of Geophysical Research: Earth*
 275 *Surface* 119(7), 1484-1497.

276 Detert, M. and Weitbrecht, V. (2012) User guide to gravelometric image analysis by
 277 BASEGRAIN. *Advances in science and research*, 1789-1795.

278 Diaz, J.C.F., Judge, J., Slatton, K.C., Shrestha, R., Carter, W.E. and Bloomquist, D. (2010)
 279 Characterization of full surface roughness in agricultural soils using groundbased LiDAR, pp.
 280 4442-4445, IEEE.

281 Gimel'farb, G. (2002) Probabilistic regularisation and symmetry in binocular dynamic
 282 programming stereo. *Pattern Recognition Letters* 23(4), 431-442.

283 Goring, D., Nikora, V. and McEwan, I. (1999) Analysis of the texture of gravel beds using 2-
284 D structure functions, pp. 111-120, Springer New York.

285 Graham, D.J., Rollet, A.J., Piégay, H. and Rice, S.P. (2010) Maximizing the accuracy of image-
286 based surface sediment sampling techniques. *Water Resources Research* 46(2), W02508.

287 Groom, J., Bertin, S. and Friedrich, H. (2018a) Assessing Intra-Bar Variations in Grain
288 Roughness Using Close-Range Photogrammetry. *Journal of Sedimentary Research* 88(5), 555-
289 567.

290 Groom, J., Bertin, S. and Friedrich, H. (2018b) Evaluation of DEM size and grid spacing for
291 fluvial patch-scale roughness parameterisation. *Geomorphology* 320, 98-110.

292 Hodge, R., Brasington, J. and Richards, K. (2009a) Analysing laser-scanned digital terrain
293 models of gravel bed surfaces: linking morphology to sediment transport processes and
294 hydraulics. *Sedimentology* 56(7), 2024-2043.

295 Hodge, R., Brasington, J. and Richards, K. (2009b) In situ characterization of grain-scale
296 fluvial morphology using Terrestrial Laser Scanning. *Earth Surface Processes and Landforms*
297 34(7), 954-968.

298 James, T.D., Carbonneau, P.E. and Lane, S.N. (2007) Investigating the effects of DEM error
299 in scaling analysis. *Photogrammetric Engineering & Remote Sensing* 73(1), 67-78.

300 Lamarre, H. and Roy, A.G. (2005) Reach scale variability of turbulent flow characteristics in
301 a gravel-bed river. *Geomorphology* 68(1), 95-113.

302 Lane, S.N. (2005) Roughness–time for a re-evaluation? *Earth Surface Processes and*
303 *Landforms* 30(2), 251-253.

304 Legleiter, C.J., Phelps, T.L. and Wohl, E.E. (2007) Geostatistical analysis of the effects of stage
305 and roughness on reach-scale spatial patterns of velocity and turbulence intensity.
306 *Geomorphology* 83(3), 322-345.

307 Mao, L., Cooper, J.R. and Frostick, L.E. (2011) Grain size and topographical differences
 308 between static and mobile armour layers. *Earth Surface Processes and Landforms* 36(10),
 309 1321-1334.

310 Millane, R.P., Weir, M.I. and Smart, G.M. (2006) Automated analysis of imbrication and flow
 311 direction in alluvial sediments using laser-scan data. *Journal of Sedimentary Research* 76(8),
 312 1049-1055.

313 Morvan, H., Knight, D., Wright, N., Tang, X. and Crossley, A. (2008) The concept of
 314 roughness in fluvial hydraulics and its formulation in 1D, 2D and 3D numerical simulation
 315 models. *Journal of Hydraulic Research* 46(2), 191-208.

316 Nelson, P.A., Bellugi, D. and Dietrich, W.E. (2014) Delineation of river bed-surface patches
 317 by clustering high-resolution spatial grain size data. *Geomorphology* 205, 102-119.

318 Nestler, J. and Sutton, V.K. (2000) Describing scales of features in river channels using fractal
 319 geometry concepts. *Regulated Rivers: Research & Management* 16(1), 1-22.

320 Nikora, V.I., Goring, D.G. and Biggs, B.J.F. (1998) On gravel-bed roughness characterization.
 321 *Water Resources Research* 34(3), 517-527.

322 Noss, C. and Lorke, A. (2016) Roughness, resistance, and dispersion: Relationships in small
 323 streams. *Water Resources Research* 52(4), 2802-2821.

324 Ockelford, A.M. and Haynes, H. (2013) The impact of stress history on bed structure. *Earth*
 325 *Surface Processes and Landforms* 38(7), 717-727.

326 Pearson, E., Smith, M.W., Klaar, M.J. and Brown, L.E. (2017) Can high resolution 3D
 327 topographic surveys provide reliable grain size estimates in gravel bed rivers? *Geomorphology*.

328 Powell, D.M., Ockelford, A., Rice, S.P., Hillier, J.K., Nguyen, T., Reid, I., Tate, N.J. and
 329 Ackerley, D. (2016) Structural properties of mobile armors formed at different flow strengths
 330 in gravel-bed rivers. *Journal of Geophysical Research: Earth Surface* 121(8), 1494-1515.

331 Qin, J. and Ng, S. (2012) Estimation of Effective Roughness for Water-Worked Gravel
 332 Surfaces. *Journal of Hydraulic Engineering* 138(11), 923-934.

333 Qin, J., Zhong, D., Wang, G. and Ng, S.L. (2012) On characterization of the imbrication of
 334 armored gravel surfaces. *Geomorphology* 159, 116-124.

335 Robert, A. (1990) Boundary roughness in coarse-grained channels. *Progress in Physical*
 336 *Geography* 14(1), 42-70.

337 Robert, A., Roy, A. and De Serres, B. (1996) Turbulence at a roughness transition in a depth
 338 limited flow over a gravel bed. *Geomorphology* 16(2), 175-187.

339 Schneider, J.M., Rickenmann, D., Turowski, J.M. and Kirchner, J.W. (2015) Self-adjustment
 340 of stream bed roughness and flow velocity in a steep mountain channel. *Water Resources*
 341 *Research* 51.

342 Smart, G., Aberle, J., Duncan, M. and Walsh, J. (2004) Measurement and analysis of alluvial
 343 bed roughness. *Journal of Hydraulic Research* 42(3), 227-237.

344 Smart, G.M., Duncan, M.J. and Walsh, J.M. (2002) Relatively rough flow resistance equations.
 345 *Journal of Hydraulic Engineering* 128(6), 568-578.

346 Smith, M.W. (2014) Roughness in the Earth Sciences. *Earth-Science Reviews* 136, 202-225.

347 Trevisani, S. and Cavalli, M. (2016) Topography-based flow-directional roughness: potential
 348 and challenges. *Earth Surface Dynamics* 4, 343-358.

349 Tuijnder, A.P. and Ribberink, J.S. (2012) Experimental observation and modelling of
 350 roughness variation due to supply-limited sediment transport in uni-directional flow. *Journal*
 351 *of Hydraulic Research* 50(5), 506-520.

352 Verhoest, N., Lievens, H., Wagner, W., Alvarez-Mozos, J., Moran, M., and Mattia, F. (2008)
 353 On the soil roughness parameterization problem in soil moisture retrieval of bare surfaces from
 354 synthetic aperture radar. *Sensors* 8, 4213 - 4248.

355 Zhang, Z. (2000) A flexible new technique for camera calibration. IEEE Transactions on
356 Pattern Analysis and Machine Intelligence 22(11), 1330-1334.

357

359 **Table 1.** Summary of the detrending methods used in gravel-bed roughness studies.

Paper	None	Linear	Bi-linear	Polynomial	Bi-quadratic	Second-order bi-quadratic	Moving-window	Not specified
Aberle & Smart (2003)		✓						
Aberle & Nikora (2006)		✓						
Aberle et al (2010)		✓						
Baewert et al (2014)								✓
Bertin et al (2013)					✓			
Bertin & Friedrich (2014)						✓		
Bertin & Friedrich (2016)		✓						
Bertin et al (2017)			✓				✓	
Bertin & Friedrich (2018)			✓				✓	
Butler et al (2001)	✓							
Brasington et al (2012)								✓
Coleman et al (2011)								✓
Cooper & Tait (2009)			✓					
Curran et al (2014)			✓					
Groom et al (2018a)			✓				✓	
Hodge et al (2009a)		✓						
James et al (2007)				✓				
Mao et al (2011)			✓					
Millane et al (2006)			✓					
Nelson et al (2014)								✓
Noss & Lorke (2016)	✓							
Ockelford et al (2013)								✓
Pearson et al (2017)		✓						
Powell et al (2016)		✓						
Qin et al (2012)		✓						
Smart et al (2002)							✓	
Smart et al (2004)							✓	
Schneider et al (2015)		✓						

361 **Figure captions**

362

363 **Figure 1.** Coefficient of variation of the standard deviation of elevations (CV) expressed as a

364 percentage for each detrending method with changes in moving-window size for the five

365 surfaces.

Figure 2. Coefficient of variation of the standard deviation of elevations expressed as a percentage for each detrending method with changes in movingwindow size for the five surfaces.

Figure 3. Standard deviation of elevations for each detrending method with changes in moving-window size for the five surfaces. Horizontal lines added to display plateau in values for moving-window detrending.

Figure 4. Skewness values for each detrending method with changes in moving-window size for the five surfaces. Horizontal lines added to display plateau in values for moving-window detrending.

Field 1 **Lab 1** **Field 2** **Lab 2** **Field 3**

378

379

Figure 5. Kurtosis values for each detrending method with changes in moving-window size for the five surfaces. Horizontal lines added to display plateau in values for moving-window detrending.

380

381

Figure 6. Inclination index values for each detrending method with changes in moving-window size for the five surfaces. Horizontal lines added to display plateau in values for moving-window detrending.

Field 1 **Lab 1** **Field 2** **Lab 2** **Field 3**

386

387 **Figure 7.** Horizontal roughness lengths in the downstream direction (L_x) determined from
 388 second-order structure functions, for each detrending method, with changes in moving-window
 389 size for the five surfaces. Horizontal lines added to display plateau in values for moving-
 390 window detrending.

Field 1 **Lab 1** **Field 2** **Lab 2** **Field 3**

391

392

393

394

395

Figure 8. Horizontal roughness lengths in the transverse direction (L_y) determined from second-order structure functions, for each detrending method, with changes in moving-window size for the five surfaces. Horizontal lines added to display plateau in values for moving-window detrending.