Geomorphology 113 (2009) 4–11

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Terrestrial Laser Scanning of grain roughness in a gravel-bed river

George L. Heritage [a], David J. Milan [a,b,*]

[a] University of Salford, Built and Human Environment Research Institute, School of Environment and Life Sciences, Peel Building, Manchester, M5 4WT, United Kingdom
[b] University of Gloucestershire, Department of Natural and Social Sciences, FCH, Swindon Road, Cheltenham, GL50 4AZ, United Kingdom

ARTICLE INFO

Article history:
Received 30 June 2008
Received in revised form 2 February 2009
Accepted 30 March 2009
Available online 6 April 2009

Keywords:
Terrestrial Laser Scanning
Roughness
Grid-by-number sampling
Grain-size
DEM

ABSTRACT

This paper demonstrates the application of Terrestrial Laser Scanning (TLS) to determine the full population of grain roughness in gravel-bed rivers. The technique has the potential to completely replace the need for complex, time-consuming manual sampling methods. Using TLS, a total of 3.8 million data points (mean spacing 0.01 m) were retrieved from a gravel bar surface at Lambley on the River South Tyne, UK. Grain roughness was extracted through determination of twice the local standard deviation ($2\sigma_z$) of all the elevations in a 0.15 m radius moving window over the data cloud. $2\sigma_z$ values were then designated to each node on a 5 cm regular grid, allowing fine resolution DEMs to be produced, where the elevation is equivalent to the grain roughness height. Comparisons are made between TLS-derived grain roughness and grid-by-number sampling for eight 2 m^2 patches on the bar surface. Strong relationships exist between percentiles from the population of $2\sigma_z$ heights with measured *a*-, *b*-, and *c*-axes, with the closest matches appearing for the *c*-axis. Although strong relationships exist between TLS-derived grain roughness ($2\sigma_z$), variations in the degree of burial, packing and imbrication, results in very different slope and intercept exponents. This highlights that conventional roughness measurement using gravel axis length should be used with caution as measured axes do not necessarily represent the actual extent to which the grain protrudes into the flow. The sampling error inherent in conventional sampling is also highlighted through undertaking Monte Carlo simulation on a population of 2000 clasts measured using the grid-by-number method and comparing this with the TLS-derived population of grain roughness heights. Underestimates of up to −23% and overestimates of up to +50% were found to occur when considering the D_{84}, and −20% and overestimates of up to +36% were found to occur when considering the D_{50}.

1. Introduction

Accurate measurement of channel boundary roughness is of fundamental importance for fluvial geomorphology and hydraulics due to its role in moderating mean flow velocity, sediment transport and turbulence. The interaction between flow and the channel boundary is highly complex and remains poorly understood despite its economic and social importance in flood level forecasting. Natural gravel-bed channels are composed of heterogeneous sized grains that are non-uniformly spaced, and that protrude into the flow to varying extents due to variable burial depth or imbrication (Kirchner et al., 1990). It is the resistance afforded by the sediment grains at the bed surface which is assumed to dominate the flow resistance (Nikurdase, 1933; Robert, 1990). Grain roughness (k_s) in gravel-bed rivers is usually estimated indirectly through measurement of the grain-size distribution of the sediments at the surface of the channel boundary, and is usually associated with a characteristic grain-size percentile of the bed material, for example D_{50}, D_{84} or D_{90} (e.g. Ackers and White, 1973; Gladki, 1979; Whiting and Dietrich, 1990; Clifford et al., 1992; Gomez, 1993). The percentile value is scaled up using an empirically determined multiplier in order to represent the equivalent k_s, to account for the non-uniform nature of gravel-bed surfaces, responsible for producing the observed energy loss when introduced into the logarithmic flow equation for rough open channels (Keulegan, 1938; Hey 1979; Whiting and Dietrich, 1991; Wiberg and Smith, 1991; Ferguson and Ashworth, 1992; Clifford et al., 1992). In practice k_s is a composite parameter dependent upon the size, shape, and spacing of roughness elements (Schlicting, 1936; Morris, 1955; Sayre and Albertson, 1963), and k_s commonly exceeds the maximum grain-size present on the bed (Kamphius, 1974; Gessler, 1990).

Characterisation of surface grain-size is notoriously problematic due to patchiness (Crowder and Diplas, 1997; Buffington and Montgomery, 1999), incompatibility between sampling approaches (Diplas and Sutherland, 1988; Fraccarollo and Marion, 1995), operational bias (Marcus et al., 1995; Wohl et al., 1996) and insufficient sample size (Church et al., 1987; Milan et al., 1999). Grain-size can vary at different spatial scales for example within a bar (Wolcott and Church, 1991), between bedforms such as pools and riffles (Milan et al., 2001), and show gradual downstream changes linked to size

* Corresponding author. University of Gloucestershire, Department of Natural & Social Sciences, FCH, Swindon Road, Cheltenham, GL50 4AZ, United Kingdom. Tel.: +44 1242 714565.
E-mail address: dmilan@glos.ac.uk (D.J. Milan).

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doi:10.1016/j.geomorph.2009.03.021

selective sorting processes and abrasion (Sambrook-Smith and Ferguson, 1995; Gomez et al., 2001). Skin roughness can also be influenced by the presence of microscale bedforms such as pebble clusters, which may not be accounted for during grain-size sampling.

Despite these issues grid-by-number sampling, using a standard surface sample of 100 clasts (Wolman, 1954) is the accepted method for estimating roughness indirectly from grain-size. The b-axis of 100 clasts are usually sampled over a patch of gravel comprising a single facies or population, 'a zone or area considered homogenous' (Dunne and Leopold, 1978, p.666), sampling being conducted over a grid or transect (Wolman, 1954). Percentiles are then extracted from cumulative grain-size distributions. Surface grain-size has also been measured using emulsion-based photography (Kellerhals and Bray, 1971; Adams, 1979; Ibbeken and Schleyer, 1986; Church et al., 1987; Rice and Church, 1998), through direct measurement at grid-selected positions on the image, or by counting visible grains and conversion to a mean grain-size via a calibration relation (Church et al., 1987; Rice, 1995). This approach can be extremely time-consuming due to the post processing required, with even the more advanced photo-sieving procedures requiring manual identification and digitisation of grain boundaries (Ibbeken and Schleyer, 1986; Diepenbrook et al., 1992; Diepenbrook and De Jong, 1994; Ibbeken et al., 1998). More recently, digital imagery and automated image processing techniques have been introduced, that provide accurate representations of grain roughness but are limited to small areas (Butler et al., 1998, 2001a; Lane, 2002, Sime and Ferguson, 2003; Graham et al., 2005), with the exception of Carbonneau et al. (2004, 2005) who have demonstrated some success in the use of aerial imagery for grain-size determination over larger areas of river channel.

The use of a single percentile D_z to represent k_s can be problematic due to the effects of 1) grain-size distribution, 2) spacing and sorting, 3) particle shape and orientation, 4) bed arrangement, 5) packing/imbrication and 6) microscale bedforms (clusters). Imbrication effectively decreases the roughness height from the bed, whereas pebble clusters tend to provide locally increased roughness height. An alternative method that takes into consideration all of these factors, is to treat the bed surface as a random field of elevations $Z(x,y,t)$, where x and y are longitudinal (main flow direction) and transverse coordinates, and t is time. This approach is more realistic as it quantifies the degree to which grains extend into the flow and thus measures actual roughness height, overcoming the issue of partial burial or imbrication inherent in conventional grain measurement approaches. Until the early 1990s the success of this approach was tempered by the lack of high-resolution topographic data covering all roughness scales (e.g. Furbish, 1987; Robert, 1988, 1990, 1991; Clifford et al., 1992). Improved data-capture is now achievable using photographic and laser scanning technology (Nikora et al., 1998; Goring et al., 1999; Butler et al., 2001b; Aberle and Smart, 2003; Marion et al., 2003; Nikora and Walsh, 2004; Smart et al., 2004; Aberle and Nikora, 2006). The application of laser scanning technology to retrieve information on grain roughness in the field however has not yet been fully explored. Terrestrial Laser

Table 1
Laser data point spacing statistics, based upon a sample of 3.8 million data points.

Mean	0.0124
25%-tile	0.0052
Median	0.0094
75%-tile	0.0159
Maximum	1.3776
Interquartile range	0.0106
Standard deviation	0.0119

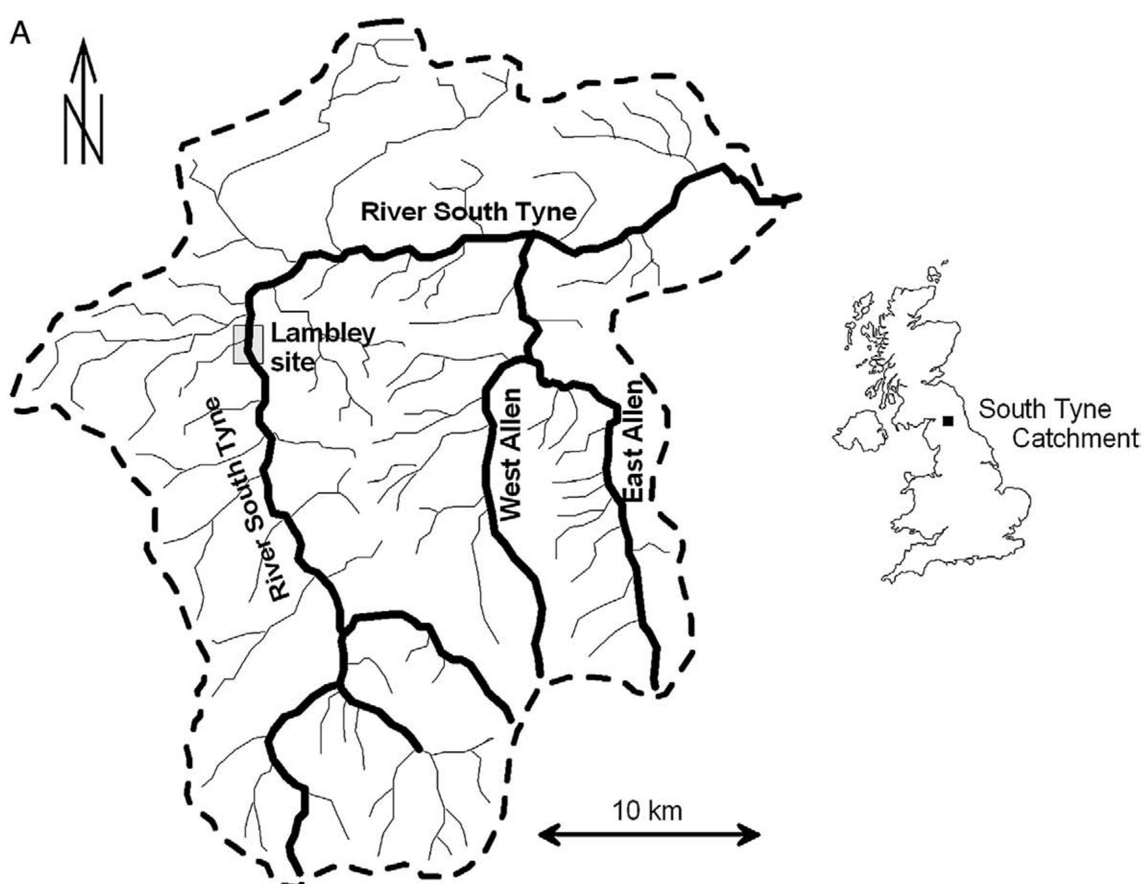

Fig. 1. River South Tyne at Lambley, A) site location, images of B) upstream and C) downstream bars.

B

C

Fig. 1 (*continued*).

Scanning (TLS) has proved to be extremely detailed (capturing between 1000 and 10,000 points/m^2), comparatively accurate (3D location errors of less than 0.02 m) and may be efficiently collected utilising differential GPS or reflector based tiepoint systems to mesh individual scan-cloud data. The resultant DEMs thus map all roughness elements from the grain-scale upwards across the entire scanned area, revealing their 3D structure and spatial distribution (Heritage and Hetherington, 2007; Milan et al., 2007). The aim of this paper is to explore the application of TLS to surface roughness quantification of a gravel bar using a random field approach, and to use TLS data to critically evaluate indirect roughness estimation from grain-size.

2. Field site and methodology

A large exposed gravel bar was required for this project. TLS requires the bar surface to be dry to get the most accurate results (Milan et al., 2007). The instrument used in this study scans obliquely, which results in areas of shadow on the lee of any incident object, in this case clasts. This issue may be overcome by setting up the TLS at an elevated position, and by taking a series of scans from different vantage points around the gravel bar, which are subsequently merged. A 180 m^2 gravel point bar located on the River South Tyne at Lambley was chosen as the study site due to the excellent visibility afforded across the bar surface from a bridge and valley side laser scan vantage points (Fig. 1). The South Tyne is a wandering gravel-bed channel (Passmore and Macklin, 2000) with a drainage area of 800 km^2. The river drains the North Pennines (altitude 893 m) and flows towards the confluence with the North Tyne at Warden. The local channel gradient at Lambley is 0.003. The geology of the catchment comprises sandstone and limestone with localised igneous outcrops, overlain in some areas by drift deposits of till and fluvioglacial outwash gravels. The channel at Lambley is laterally mobile and is incising following high rates of lateral channel movement and sediment deposition during the mid-nineteenth century and early twentieth century (Passmore and Macklin, 2000). The South Tyne is characterised by active zones of sedimentation, characterised by a multithread, wandering planform (e.g. Passmore and Macklin, 2000). Extensive metal contamination of sediments deposited in these sedimentation zones during the early nineteenth and twentieth centuries, due to lead and zinc mining, resulted in limited vegetative growth on bar surfaces further promoting their instability (Macklin and Smith, 1990).

An LMS Z-210 scanning laser manufactured by Riegl Instruments was used to collect topographic data. The instrument works on the principle of 'time of flight' measurement using a pulsed eye-safe infrared laser source (0.9 µm wavelength) emitted in precisely defined angular directions controlled by a spinning mirror arrangement. A sensor records the time taken for light to be reflected from the incident surface. Angular measurements are recorded to an increment of 0.036° in the vertical and 0.018° in the horizontal. Survey control was facilitated by RiScan Pro survey software, capable of visualising point cloud data in the field. Scans were generally restricted to 240° in front of the scanner and scans were collected with substantial overlap ensuring that the surface of the study reach was recorded from several directions. The effect of this approach is to increase the point resolution across the surface and to reduce the possibility of unscanned areas due to the shadowing effect of topographic heights along the line of each scan. Before scans were taken a total of 20 reflectors were placed on and around the study reach. These reflectors were tied into the project co-ordinate system using an EDM theodolite and these were automatically located by the RiScan-Pro software and matched to the project coordinates using a common point configuration algorithm.

The final dataset contained 3.8 million points with a mean spacing of 0.012 m (Table 1). Surface points were on average accurate to ±0.009 m (Table 2) when compared with 113 independent EDM theodolite validation points. Before the random elevation field could be interrogated any bed slope or bedform-induced trend must be eliminated. Past studies (e.g. Aberle and Nikora, 2006) have utilised least squares fitting procedures to laboratory river gravels with no bedforms. At the Lambley site both downstream bed slope and cross-section induced slopes were evident, as were occasional micro-bedforms, and there were a wide range of clast sizes. Detrending the surface elevation field in this situation is extremely problematic. An alternative approach is to identify the local standard deviation (σ_z) of the elevation data within a moving window equivalent to the largest visible clast, which in the case of the Lambley site was 0.15 m radius. The 0.15 m radius window was set to move at 5 cm intervals in x and y directions across the raw data cloud. A σ_z value was then designated to each node on a regular grid spaced at 5 cm. The small window size is assumed to be unaffected by regional surface trends. Each σ_z value was then multiplied by a factor of 2 to generate the effective roughness equivalent (Gomez, 1993; Nikora et al., 1998), thus generating an effective roughness height ($2\sigma_z$) sample in excess of 120 000. The regular grid files of $2\sigma_z$ were subsequently used to generate a 5 cm resolution grain roughness DEM of the point bar surface (Fig. 2). Visual comparison reveals an excellent link between textural facies and the surface roughness DEM with the larger

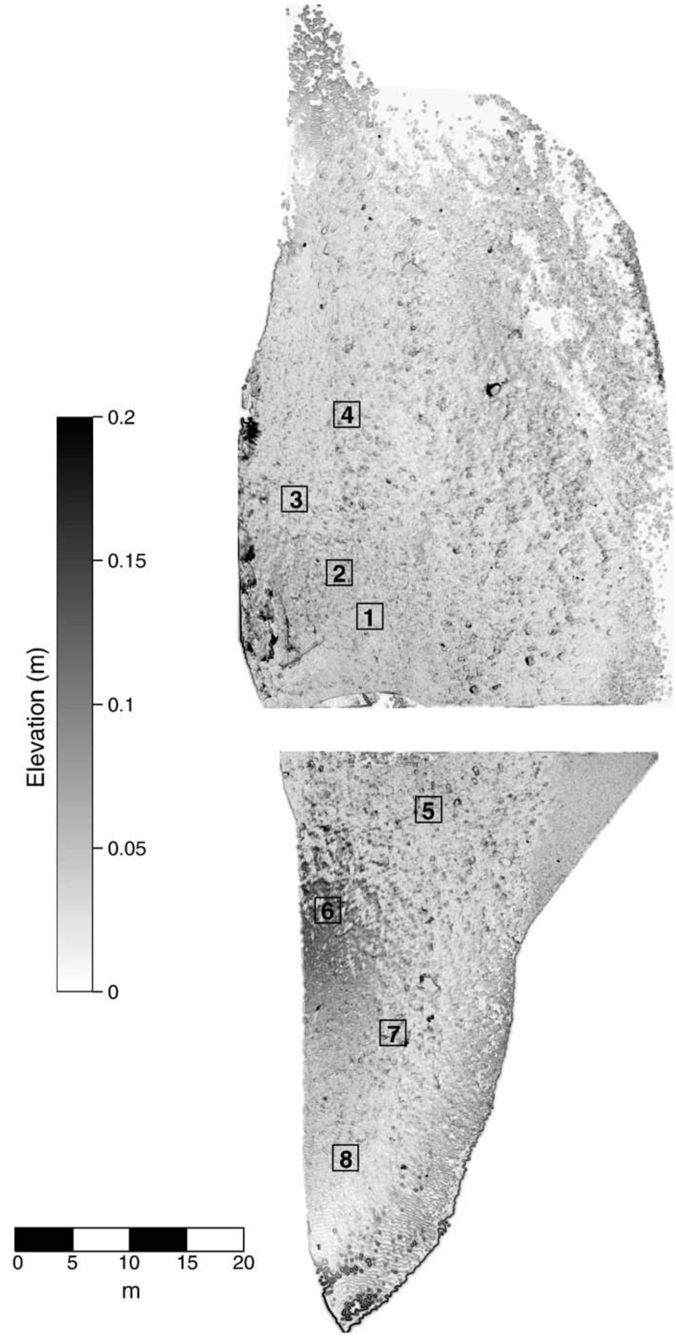

Fig. 2. Roughness height DEM ($2\sigma_z$) of upstream and downstream bar surfaces. Patch locations 1–8 are indicated.

Table 2
Laser scan elevation error statistics based on 113 independent EDM points.

Mean	6.19E−16
Median	−0.0095
Standard deviation	0.0526
Sample variance	0.0028
Kurtosis	1.9311
Skewness	0.5927

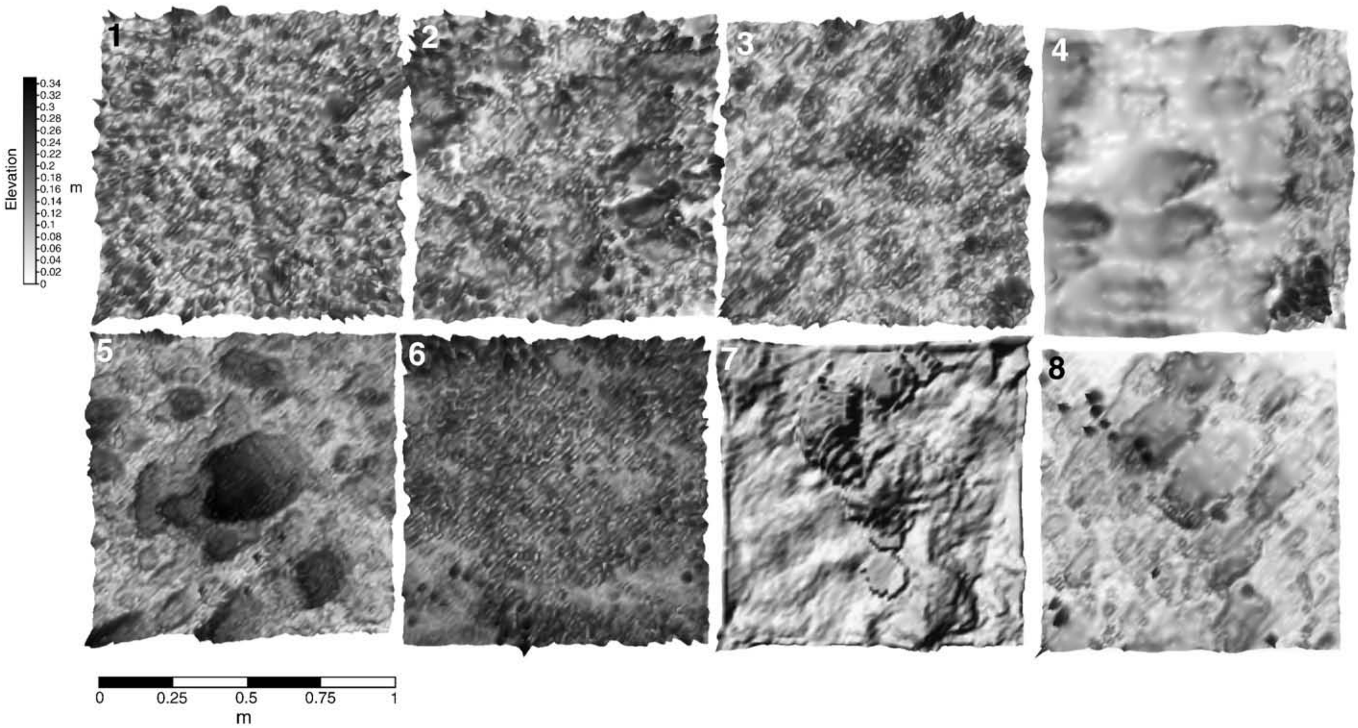

Fig. 3. Roughness height maps for gravel patches as defined from twice the standard deviation in elevation for patches 1 to 8.

sediments on the inside of the point bar and the two ridge lines of coarser material being identified (Fig. 1B,C). To create a rendered surface, Delauney triangulation with linear interpolation was employed as an exact interpolator. The population of $2\sigma_z$ were extracted for each of eight 2 m^2 sub-areas of the bar surface displaying distinct facies assemblages (Fig. 3), and the percentiles of the distribution were compared with grain-size percentiles obtained from grid-by-number sampling (see Section 3).

3. Comparison with conventional sampling

Conventional grid-by-number sampling of the long (a), intermediate (b) and short (c) axis of 100 clasts (Wolman, 1954) was also used to define the grain-size distribution at each of the 2 m^2 sub-areas, to facilitate comparison with the $2\sigma_z$ frequency distributions. Direct comparisons of grain-size (*a*-, *b*-, and *c*-axis) and TLS-derived roughness height ($2\sigma_z$) percentiles are shown in Fig. 4, where excellent linear relationships are evident ($r^2>0.8$). It is to be expected that the TLS-based measurements would show some relationship with the clast *c*-axis due to the flow orientating the primary axis in the streamwise direction exposing the shortest axis to the flow. For the relationship between the TLS-derived roughness and the c-axis measurements, patches 4, 5 and 8 yield relationships close to one-to-one. For patches 1, 6 and 7, the TLS data underestimates the *c*-axis, drastically in the case of patch 6. For patches 2 and 3 the laser data underestimates the *c*-axis at small sizes and over estimates the *c*-axis at larger sizes. The excellent relation also obtained for the *a*- and *b*-axes is surprising as these measures have no direct link to surface elevation change, as defined by $2\sigma_z$. Despite the excellent r^2 values, there is no consistency in the slope and intercept exponents between the patches. These differences could possibly relate to packing/imbrication effects. Imbrication angle can vary with clast size, shape and sphericity (Church et al., 1987). Shape analysis indicates similar shape characteristics in each of the patches, with discs dominating the shape distribution (Table 3).

The differences between the TLS-derived roughness population statistics and the conventional measured grain-size populations, are likely to be a function of variable burial depth of clasts by fines, and imbrication angle. The suggestion here is that the use of grain-size as a roughness measure is inferior to the TLS-derived data, as grain-size measurement through conventional sampling does not actually measure roughness height. Nikora et al. (1998) and Aberle and Smart (2003) argue that the σ_z of bed elevations is a better roughness scale compared to conventional D_{50} or D_{84}. Aberle and Smart (2003) found no correlation between σ_z and grain-size in their study for step-pool morphology, and concluded that σ_z was a better descriptor of roughness. Furthermore, Aberle and Smart (2003) demonstrated that σ_z was superior over the use of grain-size in their resistance equation for steep mountain streams. More recently however, Aberle and Nikora's (2006) study utilising flume and some field data from Smart et al. (2004) for armoured gravels, found that the D_{50} and D_{84} were highly correlated to σ_z, suggesting that both were equally suitable as measures of roughness height. They suggest the reason for this was the lack of bedforms.

4. Critical evaluation of roughness estimation from grain-size

If the TLS-derived elevation statistics are assumed to provide information concerning the full population for the surface gravel for a geomorphic unit, then it is possible to quantify sampling error inherent when using a traditional grid-by-number sampling approach. In total the *a*-, *b*- and *c*-axes of 2000 clasts were measured from across the bar surface; 100 clasts were measured from each of the eight patches, and a further 1200 clasts were randomly selected from the rest of the gravel bar. The *c*-axis measurements were then subject to Monte Carlo sampling to generate 512 standard grid-by-number (100 clast) grain-size distribution estimates. The *c*-axis was used in preference to the *b*-axis as several of our results for individual patches suggested a 1:1 relationship between $2\sigma_z$ and the *c*-axis. Furthermore several other authors (e.g. Johansson, 1963; Limerinos, 1970; Bathurst, 1982; Gomez, 1993) have suggested that this axis most closely relates to the roughness height, as this is usually aligned to the vertical. Comparison of the frequency statistics with the true

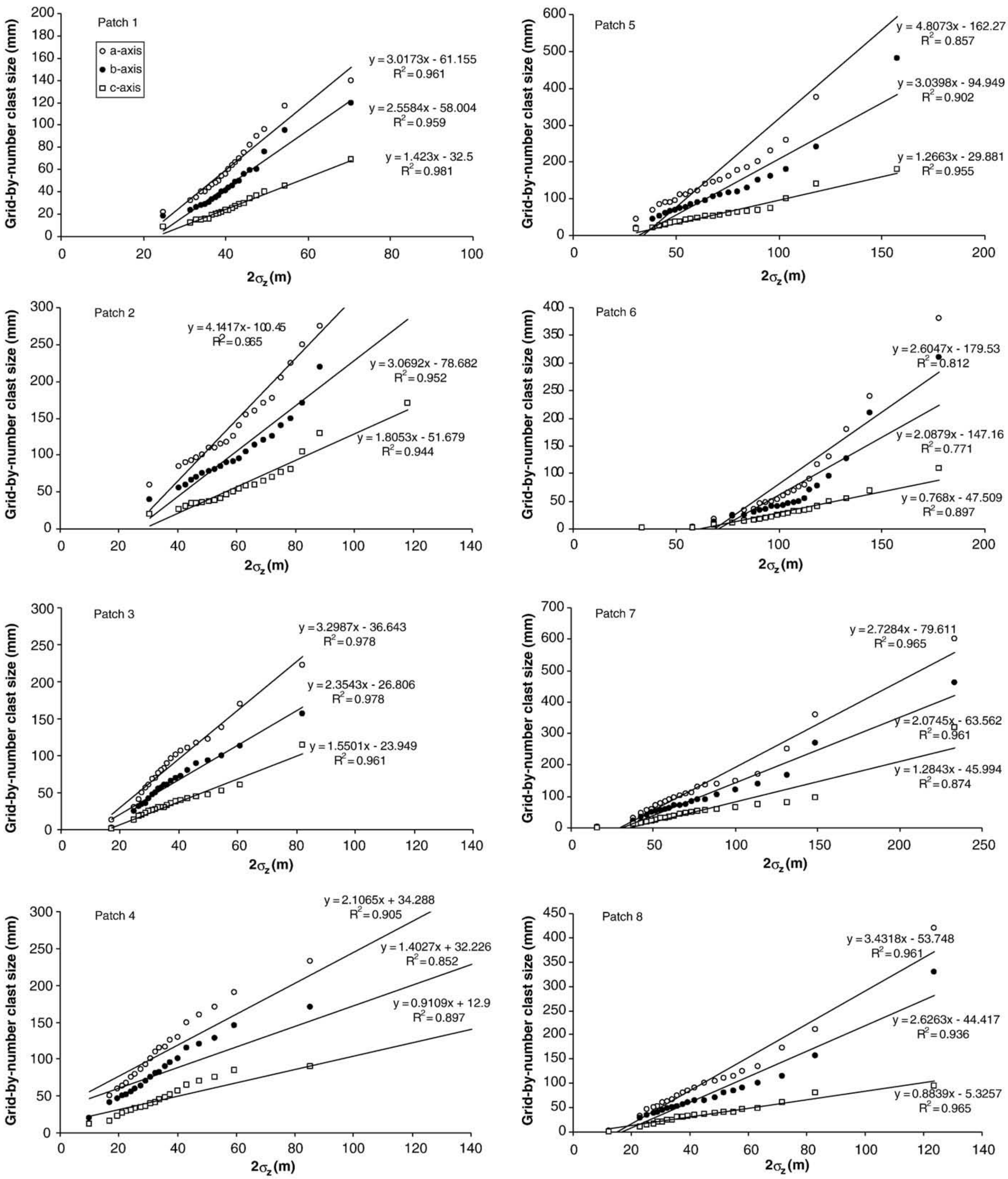

Fig. 4. Empirical relation between grid-by-number sampled clast dimensions and TLS-derived roughness height ($2\sigma_z$) from gravel patches.

distribution as defined by the entire TLS grain roughness ($2\sigma_z$) population revealed no difference between the median distribution for D_{84}, $D_{50,}$ D_{16} values (Fig. 5A). However, underestimates of up to −23% and overestimates of up to +50% were found to occur when considering the D_{84}, whilst underestimates of −20% and overestimates of up to +36% were found to occur when considering the D_{50}. The deviation away from the population estimate increased at the extremes of the grain-size distribution as would be expected as fewer very small or very large clasts would be encountered across the surface (Fig. 5B), suggesting that the Monte Carlo 100-clast re-

Table 3
Shape characteristics of patches, using Zingg (1935) classification.

	%Blade	%Rod	%Disc	%Sphere
Patch 1	13	14	54	19
Patch 2	20	19	48	13
Patch 3	22	14	50	14
Patch 4	13	13	58	16
Patch 5	18	20	55	7
Patch 6	20	21	41	18
Patch 7	17	17	48	18
Patch 8	22	13	48	17
Average	18	16	50	15

Table 4
Potential errors in D_{84}, D_{50}, D_{16} estimation, when using grid-by-number sampling for grain roughness estimation.

		Size (mm)	Error%
D_{84}	Median	130	0
	Min	100	−23
	Max	195	50
D_{50}	Median	70	0
	Min	56	−20
	Max	95	36
D_{16}	Median	40	0
	Min	26	−35
	Max	50	25

sampling of the 2000 measured clasts was not capturing the extremes of the distribution (Table 4).

5. Conclusions

Terrestrial Laser Scanning can be used to provide data on the full population of grain roughness heights for exposed bar and river bed surfaces. The technique has the potential to completely replace conventional grid-by-number sampling methods which are subject to errors related to low sample size, and sampler bias. The surface roughness recorded by the TLS relates most closely to the minor *c*-axis of clasts on the point bar surface, although the relationship was not 1:1 for all the gravel patches sampled. The nature of this relationship, as defined by the slope and intercept of the linear regression equations, also differs between patches. Although further investigation is required, this is likely to be a function of differential burial of clasts, and clast imbrication between the eight patches sampled. Thus two clasts of equivalent size may have different roughness heights as a consequence of differential imbrication and/or burial. This would suggest that conventional measurement of clast size is a poor indicator of roughness height, adding further support to the use of TLS and the random elevation field approach to roughness quantification. This investigation also demonstrates that conventional grid-by-number sampling techniques are inaccurate by between 3.0 and 8.9% in 50% of simulated sample cases with maximum errors exceeding 70%. It is argued that the random field approach should replace grid-by-number sampling wherever practicable in order to reduce the error inherent with conventional grain-size sampling.

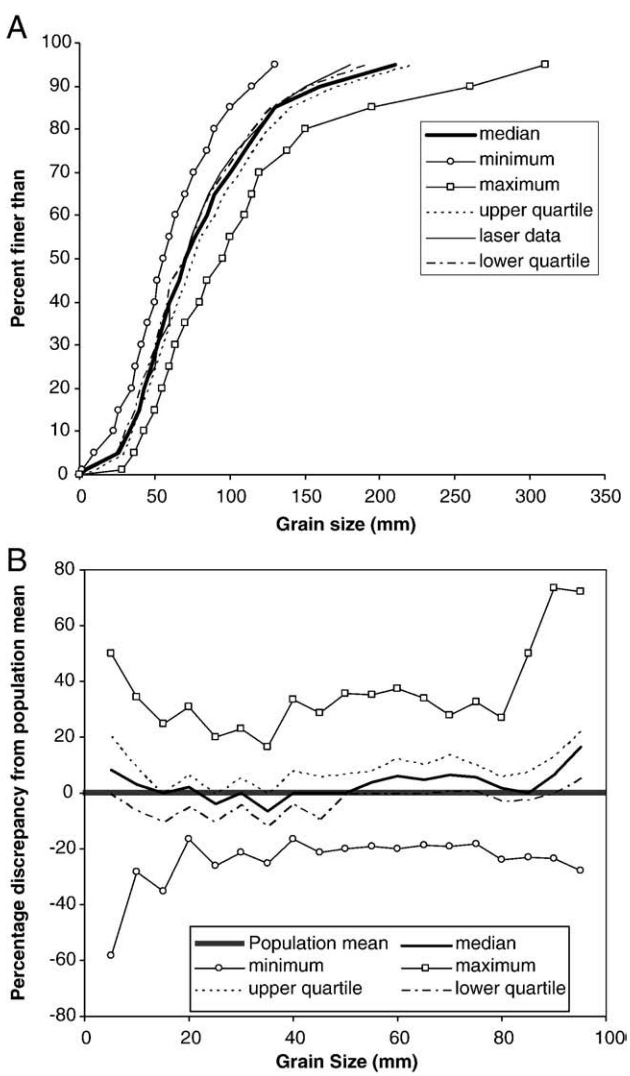

Fig. 5. Sampling error involved using the Wolman (1954) grid-by-number technique, A) differences in cumulative frequency distributions, B) percentage discrepancy from population mean. The words 'median', and 'lower/upper quartile' refer to the populations of grain-size curves generated during the Monte Carlo sampling process.

Acknowledgements

We would like to acknowledge the field assistance of Andrew Large, Ian Fuller, and Neil Entwistle. The authors are grateful to two anonymous reviewers, and the managing guest editor for their helpful comments and suggestions.

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