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Filtering spatial error from DEMs: Implications for morphological change estimation

David J. Milan [a,*], George L. Heritage [b], Andrew R.G. Large [c], Ian C. Fuller [d]

[a] Department of Natural & Social Sciences, University of Gloucestershire, Cheltenham, GL50 4AZ, United Kingdom
[b] JBA Consulting, The Brew House, Wilderspool Park, Greenhalls Avenue, Warrington, WA4 6HL, United Kingdom
[c] Earth Surface Processes Research Group, School of Geography & Politics, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom
[d] School of People, Environment & Planning Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand

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ABSTRACT

Scour and fill estimation from digital elevation model (DEM) subtraction or differencing is an increasingly common technique in morphological and sediment transport investigations. The technique is commonly used to estimate scour and fill volumes and to produce scour and fill maps that provide process-based information to geomorphologists. Accounting for sources of uncertainty within the DEM is of critical importance. DEM error is spatially variable and has a tendency to be greater at breaks of slope such as bar and bank edges. In the past however, this has been achieved using a uniform error metric across the DEM, resulting in over-conservative estimates of error. In turn this has led to over-conservative scour and fill volumes, and incorrect process interpretation. This paper applies a new approach that permits assessment of spatially distributed error across a DEM. The method is tested on a sequence of field surveys of the gravel-bed River Nent, Cumbria, UK. The results demonstrate some dramatic differences: application of conventional techniques that account for mean error across a DEM led to a 15 and 31% underestimation in scour and fill volumes, respectively, between July and October 1998, whilst for the October 1998–June 1999 subtraction 31 and 13% of scour and fill were underestimated respectively. Use of a uniform error across a surface captures less change in comparison to a spatially distributed approach. Furthermore, the changes captured using a uniform error are biased toward areas of the channel that have more local topographic variability such as bar and bank edges. In contrast the use of a spatially distributed approach provides information on change from flatter surfaces such as bar tops that would otherwise be missed. This study also demonstrates that estimates of morphological change can be misleading in the absence of an error filter. Where the raw survey data is available, it is recommended that sediment budgeting studies take account of the spatial variability of error in each DEM involved in the subtraction.

1. Introduction

The use of digital elevation models (DEMs) to represent topographic surfaces is increasingly common in geomorphology with the development of field survey hardware allowing spatially distributed and morphologically based survey data to be captured—e.g., total stations (Fuller et al., 2003, 2005), dGPS (Brasington et al., 2000, 2003; Wheaton et al., 2009a), aerial LiDAR (Charlton et al., 2003; Devereux and Amable, 2009), and terrestrial laser scanning (Milan et al., 2007; Heritage and Large, 2009; Heritage and Milan, 2009; Hodge et al., 2009)—and with the development of GIS tools capable of handling large datasets, permitting rapid interpolation and DEM production. Repeat surveys of river reaches are often conducted in order to establish both the spatial patterns of erosion and deposition and changes in volume (scour and fill). When successive DEMs are subtracted from one another, a DEM of difference (DoD) is produced that highlights areas of scour and fill (e.g., Lane et al., 2003). Volumes of scour and fill are easily extractable from many GIS software packages. Whilst the spatial distribution of geomorphologically based survey data is an undoubted improvement on previous cross section interpolation techniques (Brewer and Passmore, 2002), there is a need for increased scrutiny toward the reliability of scour and fill estimates derived from DoD, as the use of the technique both in geomorphology and ecohydraulics is expanding rapidly (e.g., Wheaton et al., 2009b).

1.1. Errors in DEM production

A number of factors can introduce error into the DEM including survey point quality, sampling strategy, surface composition, topographic complexity and interpolation methods (Lane et al., 1994; Lane, 1998; Wise, 1998, 2007; Wechsler, 2003; Hancock, 2006; Weschsler and Kroll, 2006). The quality of the raw survey data is an important consideration. The accuracy of the individual data points

* Corresponding author. Tel.:+44 1242 714565.
E-mail address: dmilan@glos.ac.uk (D.J. Milan).

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surveyed in the field is influenced by both systematic (e.g., accuracy of the survey equipment or incorrect survey rod height when surveying with a total station), and random errors (e.g., pole tilt when survey with a total station, or triangulation when surveying with a dGPS). Survey point density and spatial distribution across the surface relative to the morphology are also very important; factors that may vary between surveys. Heritage et al. (2009) demonstrated the importance of using a morphologically based survey strategy whereby the top and base of banks and bar edges are surveyed, accompanied with spot heights on bar tops and the channel bed. This survey strategy returned lower elevation errors in comparison to a regular grid-style survey of an equivalent resolution to aerial LiDAR, and other strategies including cross-sections. In addition, these workers demonstrated that survey error was uneven across a surface, with low error across uniform surfaces and increased error associated with breaks of slope such as banks and bar edges.

1.2. Interpolation artefacts

The interpolation algorithm used to model survey data can also introduce artefacts to the DEM (Goovaerts, 2000, 2001; Lloyd and Atkinson, 2001; Siska and Hung, 2001; Kastens and Staggenborg, 2002; Chaplot et al., 2006; Yue et al., 2007; Heritage et al., 2009). It is essential that surface composition and topographic complexity are considered prior to selecting an interpolation algorithm. Surface data of morphological features is often irregularly distributed across the surface in order to account for morphological features or breaks of slope. In fluvial geomorphology Delauney triangulation or TINs are often used (e.g. Brasington et al., 2000; Butler et al., 1998; Valle and Pasternack, 2006; Milan et al., 2007; Rumsby et al., 2008) or kriging (Fuller et al., 2003; Nicholas, 2003). Both of these schemes have been suggested as being the best interpolators for landscape surface data (Holmes et al., 2000), with TINs being computationally efficient and well suited to discontinuous shapes such as ridges, and breaks of slope (Moore et al., 1991). Heritage et al. (2009) have also demonstrated that TINs and kriging return lower elevation errors in comparison to other interpolation schemes in their survey of gravel bar morphology. In addition, interpolation errors are known to be spatially autocorrelated resulting in artefacts in the DEM (Wood and Fisher, 1993; Carrara et al., 1997; Wise, 1998, 2007; Guth, 1999; Heritage et al., 2009).

1.3. Uniform error assessment

Work on DEM error in river studies has tended to concentrate on elevation accuracy. Quantifying the accuracy of DEMs generated from survey data is difficult since validation requires comparison between the derived DEMs and a second, more accurate surface (Wood, 1996; Brasington et al., 2000, 2003). Usually the acquisition of this surface is impossible, therefore DEM validation is often based on quantifying model uncertainty through diagnostic surface visualisations or field "ground truthing" (Wood, 1996; Wechsler, 2000). A number of fluvial studies have accounted for errors in the DEM through comparing the DEM with check data, with the results reported as root mean square error (RMSE) (Brasington et al., 2000, 2003; Lane et al., 2003; Milan et al., 2007). In studies that involve DEM subtraction to calculate

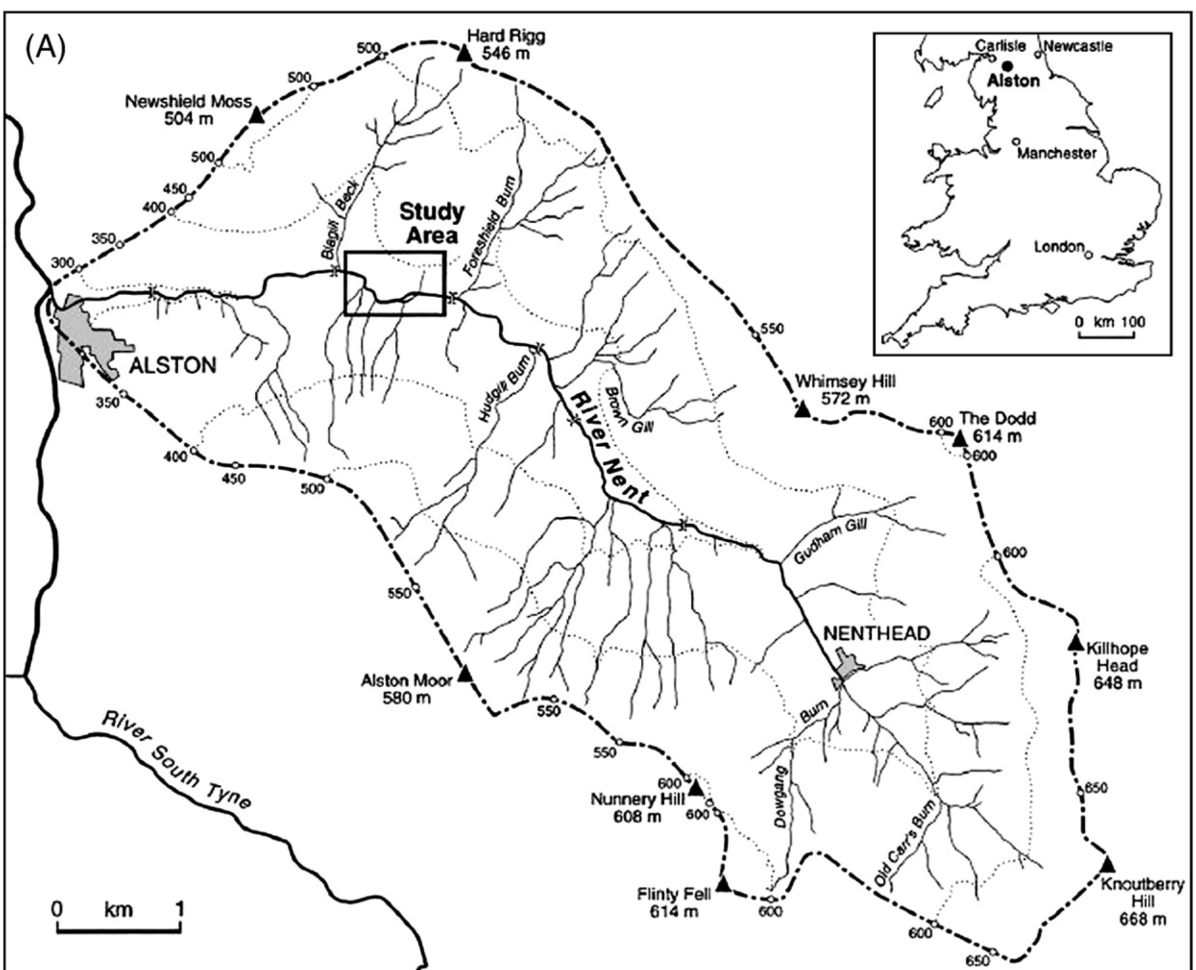

Fig. 1. Study location, Blagill, River Nent, Cumbria. (A) Catchment map, (B) study reach showing upstream and downstream in stability zones and key bar units referred to in the text.

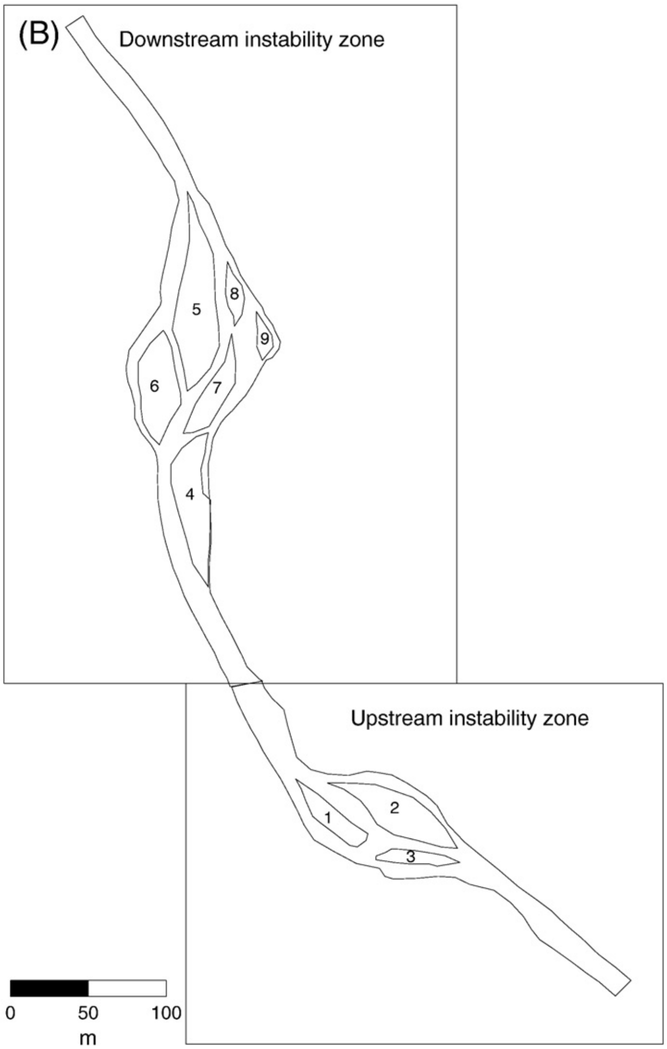

Fig. 1 (*continued*).

Table 1
Survey data for Blagill, River Nent; number of points surveyed and point density.

	No. of observations	Point density pts/m^2
July 1998	2575	0.11
October 1998	2048	0.09
June 1999	3981	0.17

sediment budgets, a level of detection (LoD) is calculated using the RMSE in each DEM to account for the propagated error in both surfaces. A key limitation with this approach is that the RMSE statistic is either averaged across the whole surface, or varies spatially only on the basis of wet and dry areas (Brasington et al., 2003; Milan et al., 2007). This practice may result in under- and/or overestimates of elevation changes in some parts of the DEM. Loss of valuable information concerning channel change and scour/fill volumes may result in areas of the DEM where the mean error is in excess of the change being measured. This is of crucial significance in fluvial geomorphology when bed changes are often very subtle in nature over a single event ($\pm$0.25 m). Assessment of the spatial distribution of error within a DEM is therefore pertinent to improving scour and fill calculation from DoD and to producing more realistic spatial representations of morphological changes exhibited in the DEM. Methods that take into consideration the spatial pattern in DEM errors are needed to better represent morphology and morphological changes.

1.4. Spatial error assessment

Methods that account for spatially distributed error in DEMs are limited. Through comparison of DEMs produced using a range of survey strategies and interpolation schemes, with a control surface generated from a terrestrial laser scan of a bar surface, Heritage et al. (2009) were able to propose a family of curves relating combined survey and interpolation error to local topographic variability. The magnitude of elevation error showed a strong dependence upon local topographic variability, and the nature of the relationships varied depending upon survey strategy and interpolation scheme.

Wheaton et al. (2009a) also present a technique for estimating the magnitude of DEM uncertainty in a spatially variable manner through

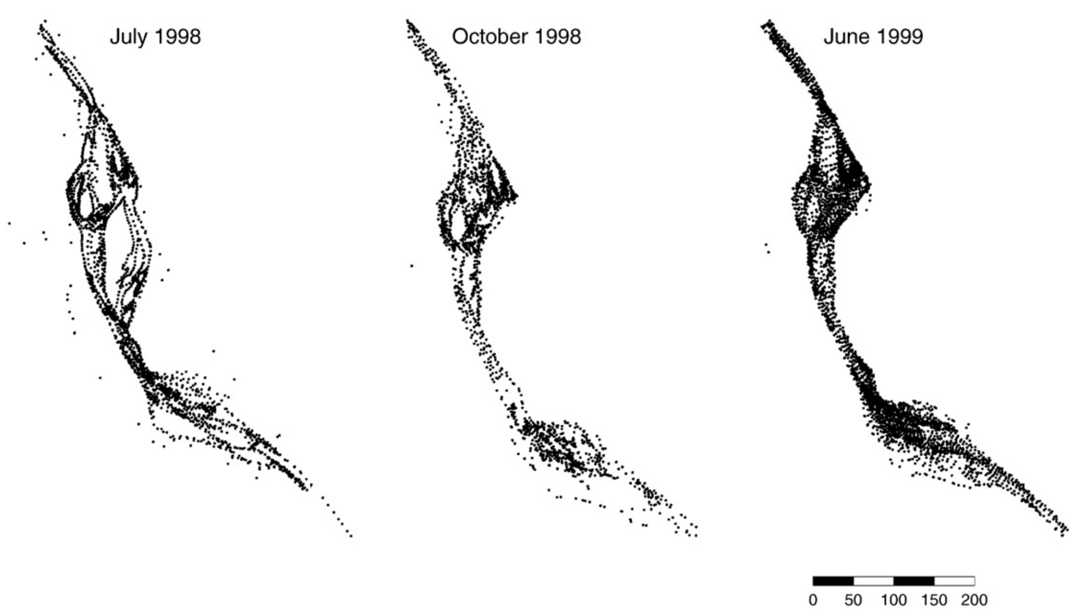

Fig. 2. Point distribution for the total station surveys conducted on the Nent at Blagill, in July 1998, October 1998, and June 1999.

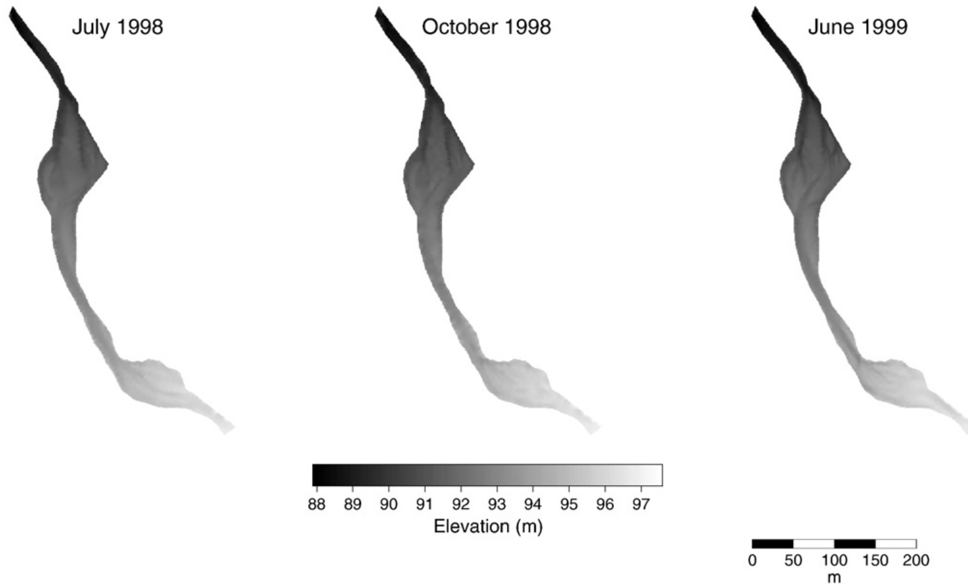

Fig. 3. DEMs constructed from the raw point data, before error assessment, for July 1998, October 1998, and June 1999.

the use of fuzzy set theory coupled with a method for discriminating DoD uncertainty on the basis of the spatial coherence of erosion and deposition using Bayes Theorem. These tools are packaged together into Matlab software. These workers suggest that various components of elevation uncertainty are collinear variables and do not exhibit a single monotic relationship to elevation uncertainty, and therefore apply a heuristic approach to the problem.

The driving observations behind the Heritage et al. and Wheaton et al. methods are similar; greater uncertainty is found in areas that have high topographic variability (high grain and/or form roughness), and that have low point density. In contrast, areas that are flat and have high point density have relatively low elevation uncertainty. Point density is implicitly accounted for in the Heritage et al. (2009) method through consideration of point survey strategy. Wheaton et al.'s method uses a fuzzy inference system (FIS) that accepts the inputs that are readily available (e.g., point density, slope, and 3D point quality) and produces σ_z output that is calibrated using field data to the range of empirically determined values.

The spatial coherence of deposition and erosion compliments the FIS procedure. The DoDs are analysed using a moving window approach to assess the characteristic shape and extent of erosion or depositional units, e.g., crescent shape bank erosion units, wide, diffuse edged features characteristic of depositional units. Areas on the DoD with these characteristic patterns are assigned a higher probability of the change taking place in comparison to those areas that do not exhibit a pattern. In summary, these workers identified less conservative volumetric estimates, in comparison to using a spatially uniform LoD, and more plausible and physically meaningful results.

A restriction with the Heritage et al. (2009) approach is that the curves calculate mean error, which restricts comparison with some of the other methods. This paper builds on Heritage et al. (2009) and presents a new approach that accounts for spatially distributed error in a DEM, through an assessment of the relationship between the standard deviation of elevation errors and local topographic roughness. The performance of the approach is tested through a comparison of the spatial patterns of scour and fill and volumetric changes

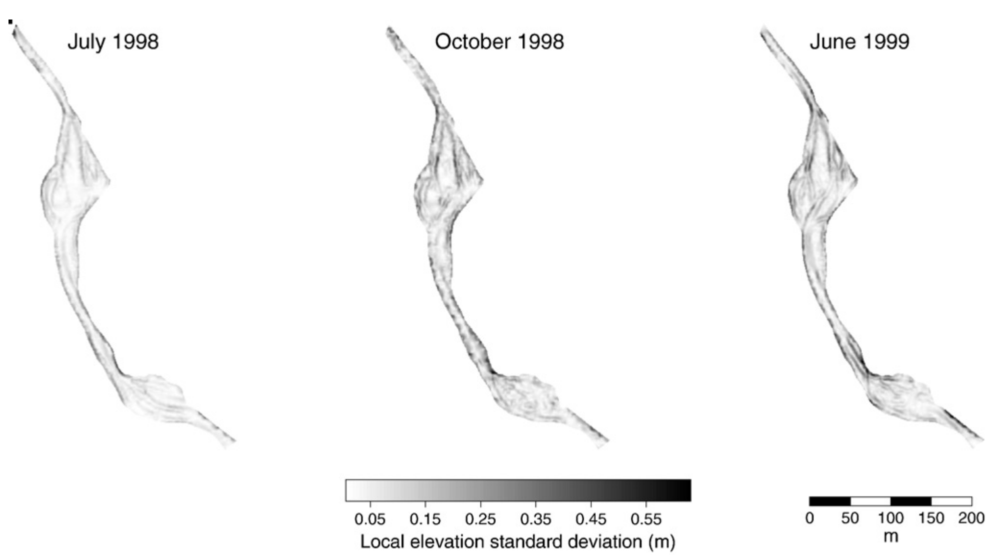

Fig. 4. Maps of topographic variability as defined through a moving window analysis over the raw point cloud data. The standard deviation of elevations within a 1-m radius moving window was attributed to grid nodes at a 0.1-m resolution, and then maps were produced.

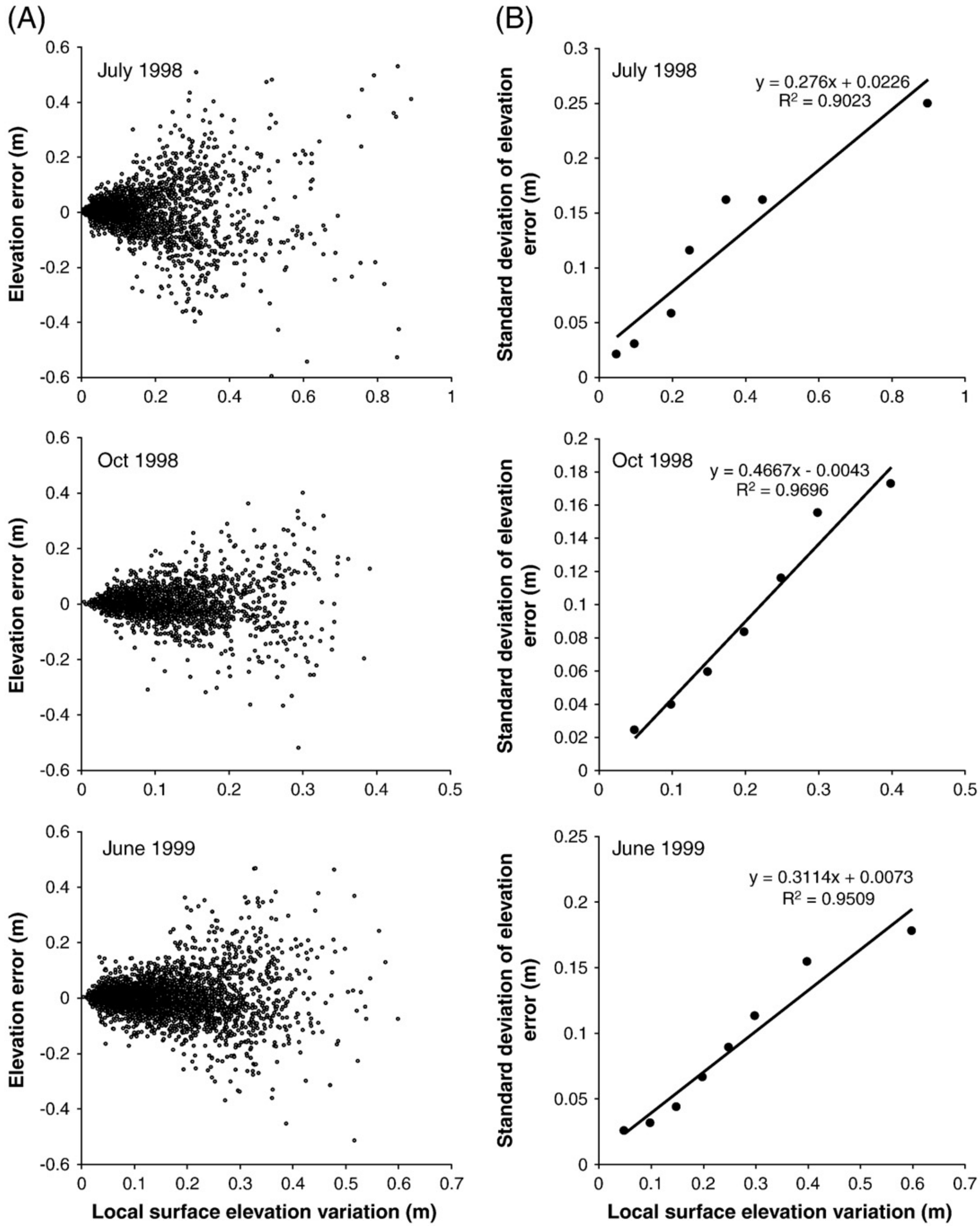

Fig. 5. Variation in elevation errors with local topographic variability, (A) raw elevation errors for each point for the three surveys, (B) standard deviation of elevation error plotted against local topographic variability.

obtained using the raw DoD and conventional application of uniform error to the DoD, for a series of river-bed surveys taken between 1998 and 1999 on the River Nent in Cumbria, UK. The key aim of this paper is to highlight (i) the importance of accounting for spatially distributed error when estimating scour and fill volumes through DEM differencing, and (ii) the improvements in process-based interpretation that can be made that would otherwise be hidden using over-conservative error assessments.

2. Study area

The study site at Blagill (Ordnance Survey Grid Reference NZ 743469) is located on the River Nent in the North Pennines (Fig. 1A). It drains an upland catchment of 29.4 km^2 before flowing into the River South Tyne, west of Alston. The geology of the basin consists of sedimentary rocks (principally sandstone, shale, and limestone) that have undergone extensive base metal mineralisation. The river may be described as wandering in nature following the criteria set out by Church (1983). The study reach has a total area of 22780 m^2 and is split into two instability zones 0.2–0.3 km in length, which are separated by a stable, single-thread reach of 150 m (Fig. 1B). Planform change and bar activity are evident in both the upper and lower instability zones creating a dynamic assemblage of morphologic units.

2.1. Upstream instability zone

This is the smaller instability zone of the two (8426 m^2) consisting of three primary bar units (Fig. 1B). The zone is composite in nature and displays extensive evidence of sediment erosion and chute channel development. Bars 1 and 3, toward the left bank of the

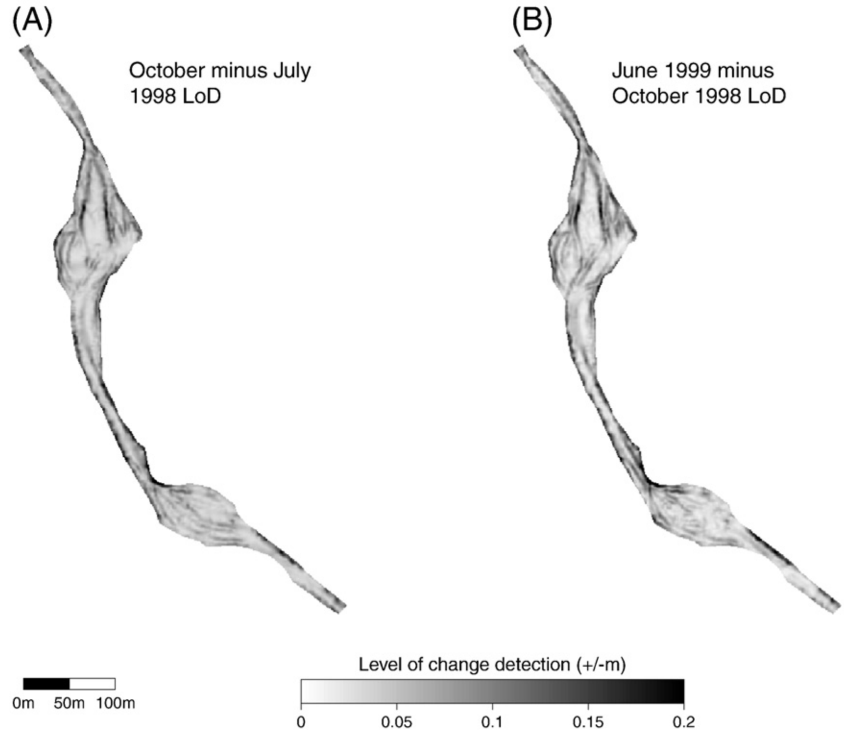

Fig. 6. Maps of spatial distribution in the level of detection. The grid files for these maps are produced firstly through transforming the standard deviation grids (Fig. 4) to grids of vertical error using the appropriate transformation from Fig. 5B to each survey grid file, and then through application of Eq. (1) to the new transformed grid files.

instability zone, are low relief features extending only 0.1 to 0.3 m above the summer low flow water surface and grading into riffle heads at their downstream ends. Bar 2 is larger and displays several surfaces ranging in elevation from 0.1 to 0.5 m above the low flow water surface on a vegetated surface close to the right bank of the instability zone.

2.2. Downstream instability zone

The second instability zone is larger (14354 m^2) and more complex, comprising four principal bar units (Fig. 1B): an extension of the point bar complex at the entrance to the reach (bar 4) and a large mid-channel bar sequence (bar 5) bounded by bar complexes on either side close to the left and right banks of the unstable zone (bars 6 and 7). Bar 4 consists of the downstream extension of the right bank point bar, heavily dissected by distributary channels as the flow crosses the channel from the left to the right bank. This process formed small low relief active gravel bars alternating with steep riffle fronts. Bar 5 is the largest feature in the downstream instability zone and is characterised by several higher bar surfaces (towards the upstream end of the feature) that are well vegetated. Sediment transport activity is evident on lower surfaces that represent the eroded remnants of larger bars and these surfaces remain unvegetated. Bar dissection is also evident, particularly on the distal surface of the feature where several chute channels can be identified. Bar 6, toward the left bank of the unstable zone, is an older feature; while bar 7 is a small lower elevation feature that has evolved significantly over the two years of survey.

3. Methods

In this investigation we reanalyse river-bed survey data first reported in Chappell et al. (2003). Elevation was measured relative to an arbitrary datum, which remained consistent during the lifetime of the study, from July 1998 to June 1999 and allowed investigation of channel change between these dates. The sampling points were located by a conventional tacheometric survey. A Sokkia “total station” theodolite EDM (electronic distance measure) and reflector system minimized systematic error and generated the x, y, and z coordinate data of the samples relative to a consistent local coordinate system. Measurement precision was ± 5 mm. The locations of the elevation observations for each of the surveys are illustrated in Fig. 2 and were based on several factors believed to be important in representing the surface of the features or reach being mapped. The survey area was extended beyond the boundary of these features to minimize the effect of sparse sampling near to their edges. The survey in October 1998 followed a significant rainfall event within the Nent catchment that resulted in flood conditions within the study reach. The effects of a series of lower flow geomorphologically effective events were captured by the July 1998 and June 1999 surveys.

The location of survey points relative to the morphology being surveyed (the field survey sampling strategy) can significantly influence DEM error (Heritage et al., 2009), with errors increasing at breaks of slope. Although point densities are much lower, field surveys using total station or dGPS actually have an advantage over LiDAR in this regard, as survey points can be selected by the surveyor. This study followed a morphologically based survey strategy whereby breaks of slope were surveyed, e.g., tops and bases of bank and bar edges, and spot heights were surveyed on bar tops and in the channel. The number of observations varied between surveys and between the upstream and downstream reaches (Table 1). For each of the surveys, DEMs were constructed using kriging with linear interpolation to model the spatial data (Fig. 3).

4. DEM error

4.1. Approach 1: Uniform error

The process of DEM subtraction must account for survey errors in both surfaces. In gravel-bed rivers, some workers have used the surface grain size D_{84} as a measure of acceptable error and have presented raw volumetric change data based upon the standard

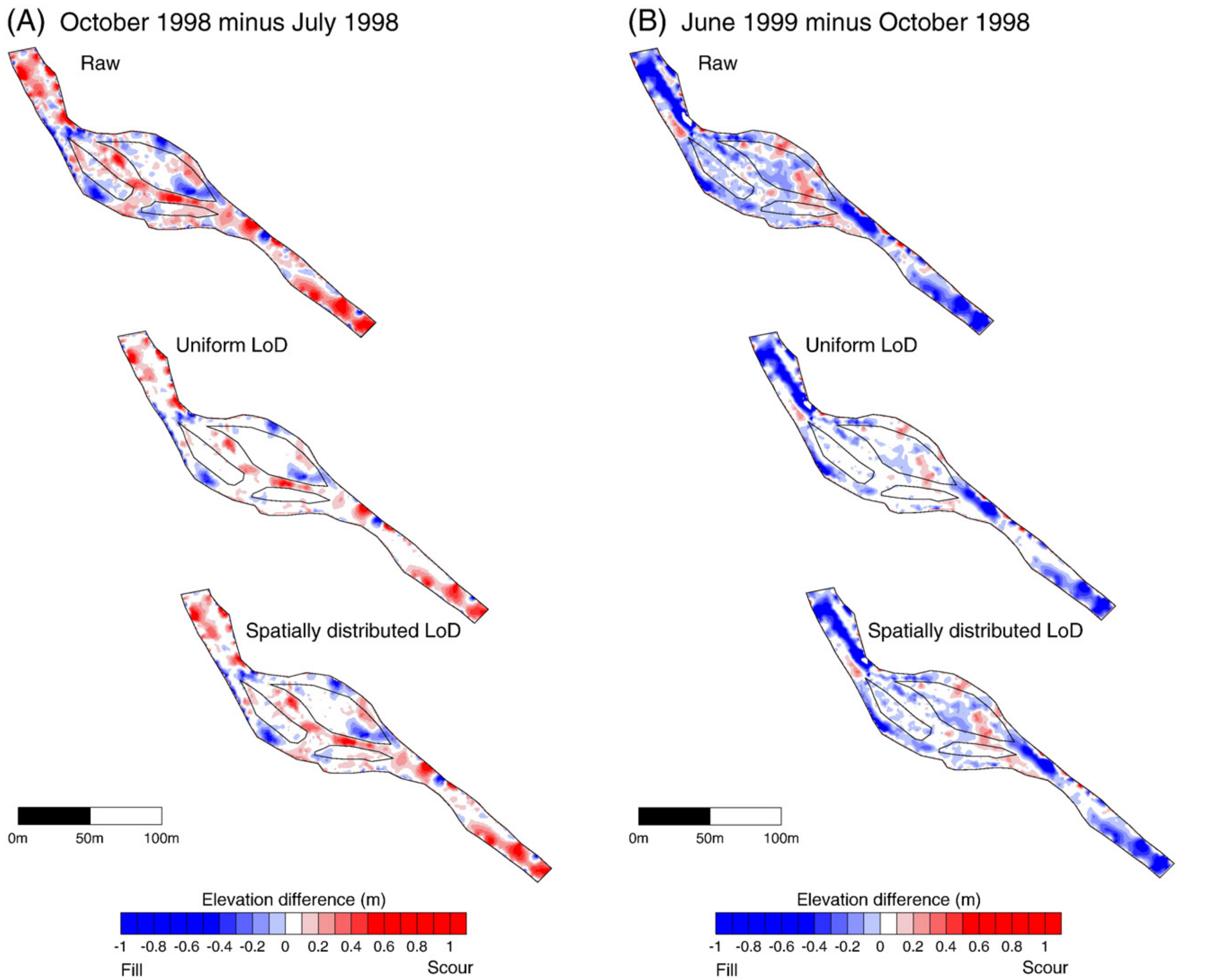

Fig. 7. DEMs of difference for the upstream instability zone, after consideration of spatial error using the new method proposed in this paper for (A) October 1998 minus July 1998, and (B) June 1999 minus October 1998.

deviation of a measured point from an interpolated point falling within the D_{84} value (e.g., Chappell et al., 2003; Fuller et al., 2003). More sophisticated procedures that deal with propagated error within each DEM used in the subtraction, have also been presented (e.g. Brasington et al., 2000, 2003; Lane et al., 2003; Milan et al., 2007). These workers account for the RMSE in each surface by using

$$U_{crit} = t\sqrt{(\sigma_{e1})^2 + (\sigma_{e2})^2} \quad (1)$$

where U_{crit} is the critical threshold error; and σ_{e1} and σ_{e2} are the standard deviation of elevation error in the raw survey data, for each surface respectively (assuming a Gaussian distribution of errors); and t is the critical t value at the chosen confidence level. This procedure may be used to derive a level of significant change detection (LoD) that can be applied to the DoD before calculation of volumetric changes. The t value may be set at $t \geq 1$ (1σ), in which case the confidence limit for the detection of change is 68% (e.g., Lane et al., 2003), or at $t \geq 1.96$ (2σ), in which case the confidence limit is equal to 95% (e.g., Brasington et al., 2000, 2003). Normally this procedure uses an average σ_e value for each surface, resulting in a uniform LoD being applied to the DEM of difference (Brasington et al., 2000, 2003; Lane et al., 2003; Milan et al., 2007).

In this study elevation errors for each survey point were obtained through a comparison of the actual elevations with the modelled surface, for each of the three surveys. Errors were found to approximate to a Gaussian distribution for the three surveys considered. The standard deviation of errors for the three surveys were as follows: $\sigma_e = 0.092$ for July 1998, and $\sigma_e = 0.069$ for both October 1998, and July 1999. Following the application of Eq. (1), an average LoD of 0.223 m was applied to the October minus July 1998 DoD grid, and an LoD of 0.192 m was applied to the July 1999 minus October 1998 DoD grid.

4.2. Approach 2: Spatially distributed error

The aim of this new approach was to develop a spatially distributed LoD that could be applied to a DoD to produce more realistic maps of change and better scour and fill volumes. The approach involved a number of steps:

(1) Local surface topographic variability was established, through defining the local elevation standard deviation (σ_z) in a 1-m radius moving window over the raw survey data (point cloud). During the moving window process, a zero value was recorded for areas with less than eight data points present in the window. A new grid of σ_z was then produced through assigning the σ_z values to each node on a 0.1-m grid (Fig. 4). The standard deviation DEMs demonstrate that the highest values are located at breaks of slope such as bar and bank edges.
(2) A local topographic roughness (σ_z) value is extracted from the σ_z grid for each x, y survey coordinate.

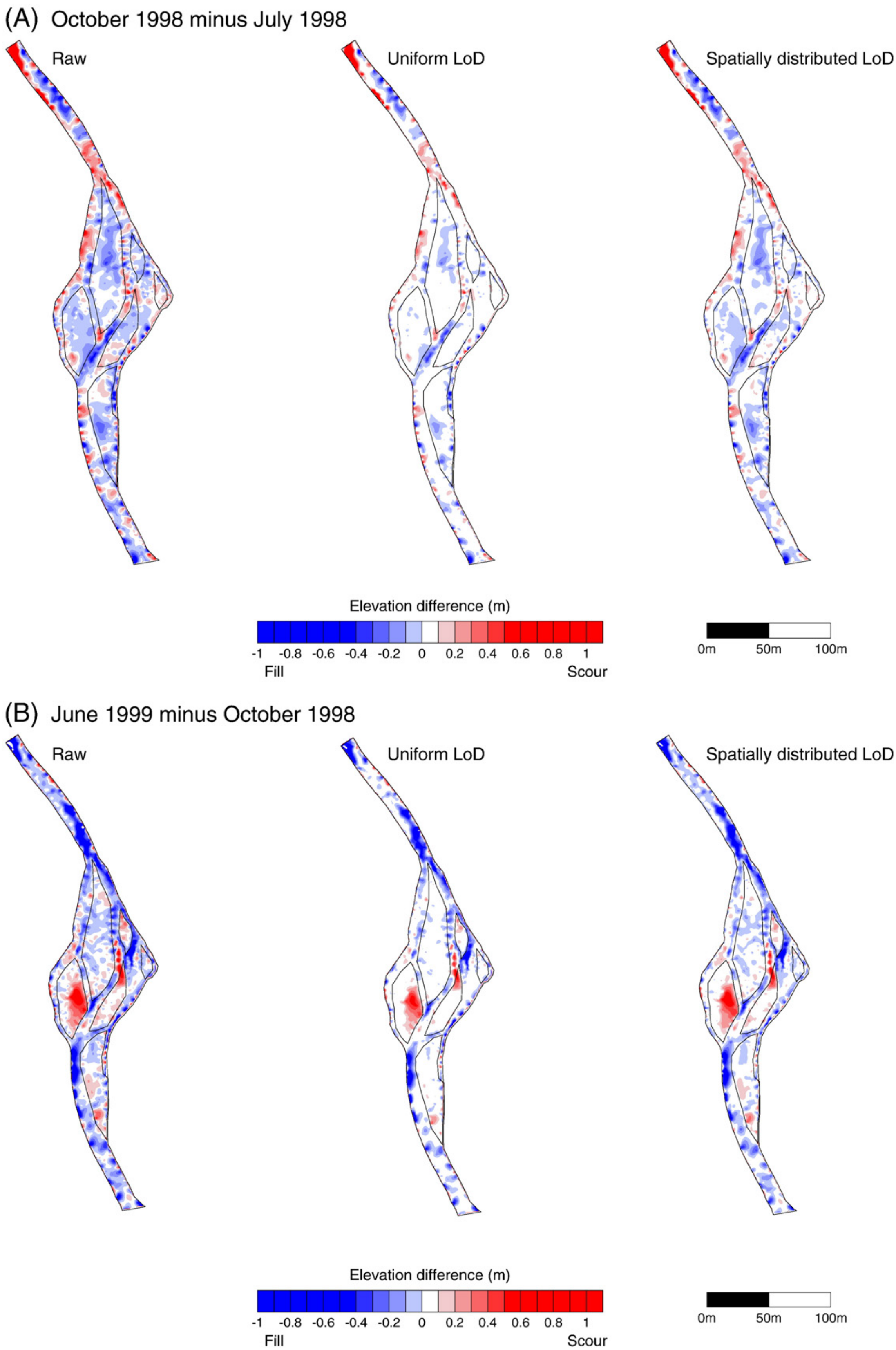

Fig. 8. DEMs of difference for the downstream instability zone, after consideration of spatial error using the new method proposed in this paper for (A) October 1998 minus July 1998 and (B) June 1999 minus October 1998.

(3) Elevation errors for each coordinate are established from the difference between modelled and measured elevations. The plot of elevation error against local surface variability as shown in Fig. 5A, indicates smaller elevation errors (±0.1 m) for flatter areas where the local topographic variation is <0.2 m (e.g., bar surfaces). Much greater scatter and larger elevation

Table 2
Erosion and deposition volumes calculated from DEM subtraction for the River Nent upstream instability zone for October minus July 1998 and June 1999 minus October 1998.

		Raw DEM	Uniform LoD based on D_{84} (0.2 m) (Chappell et al., 2003)	Uniform LoD LoD (Oct–Jul 98): 0.226 m LoD (Jun 99–Oct 98): 0.192 m	Spatially distributed LoD
Nent Oct 98–July 98	Deposition (m^3)	346.66	178.26	163.16	214.01
	Erosion (m^3)	1171.96	642.18	752.06	820.15
Nent June 99–Oct 98	Deposition (m^3)	1152.41	718.54	731.68	853.01
	Erosion (m^3)	353.38	135.25	140.89	219.06

The table demonstrates the volumes calculated (a) using the raw DEMs, before applying an LoD; (b) after a uniform LoD based upon the D84 of the bed surface was applied; (c) after a uniform LoD using a standard deviation of error (σ_e) was applied to each surface, and (d) using the spatially distributed error approach.

error is found for areas with greater local topographic variability (>0.2 m), e.g., bar edges. To aid comparison with approaches used to characterise DEM error in other studies, the σ_e needs to be considered.

(4) Using the data in Fig, 6A, the σ_e was established for different classes of topographic roughness (σ_z). The relationship between σ_e and σ_z is plotted in Fig. 5B.
(5) The linear regression equations shown in these plots were applied to the standard deviation grids (Fig. 4) to produce spatial error grids for each survey.
(6) Eq. (1) was then applied to the spatial error grid files used in the DEM subtraction, using a t value at the 95% confidence limit. This procedure generates a spatially distributed LoD grid (Fig. 6), one for each DoD.
(7) The LoD grid file is then subtracted from the raw DoD grids. The resultant grids can then be plotted as DoDs that take into consideration the spatial error in each of the component DEMs.

4.3. Effect of the filtering process

The effects of using different error filters: raw DEM, uniform LoD (Approach 1), and a spatially distributed LoD (Approach 2), are highlighted in the DoDs for the upstream instability zone in Fig. 7. The changes shown in Fig. 7A result from a large flood during October 1998 and the minor flows that followed. Use of no error filter on the DoD (raw DEM subtraction) results in striking differences compared to those DoDs that have been filtered. Much of the change shown in the raw DEM subtraction is within propagated error bounds of the DEMs used in the subtraction, and hence may not be relied upon. Use of a uniform LoD captures less change in comparison to the spatially distributed LoD approach. Subtle changes on areas of low relief such as bar tops (e.g., bars 1 and 3), are not picked up as successfully using the uniform LoD in comparison to the spatially distributed error approach.

Changes to the downstream instability zone are shown in Fig. 8. The effect of using different error filters again is apparent, with the raw DoD showing overestimates of scour and fill. The majority of the changes shown on bar surfaces between all three survey dates are shown to be within the propagated error bounds of the DEMs. Use of a spatially distributed LoD provides more detail of morphological change in comparison to the use of a uniform LoD, further supporting the same observation made for the upstream instability zone (Fig. 7).

4.4. Volumetric changes

Volume changes between successive surveys were calculated to establish the temporal losses and gains of sediment within each of the instability zones. Tables 2 and 3 demonstrate erosion and deposition volumes for the upstream and downstream instability zones, calculated from (i) raw DEMs, (ii) after taking into consideration a LoD based upon the D_{84} of the surface sediments, (iii) a uniform LoD based upon averaged RMSE (Approach 1), and (iv) spatially distributed LoD (Approach 2). The results demonstrate some dramatic differences. Failure to employ an appropriate LoD resulted in a 55 and 74% overestimate of scour and fill respectively for the October 1998 minus July 1998 survey (both reaches combined) and a 42 and 59% overestimate of scour and fill respectively for the June 1999 minus October 1998 survey. Taking into consideration the combined erosion and deposition volumes for the upstream and downstream reaches, application of a uniform LoD based on a D_{84} value of 0.2 m for the October 1998 minus July 1998 subtraction yielded a 20 and 23% underestimation for scour and fill volumes respectively, whilst for the June 1999 minus October 1998 subtraction there was a 34 and 15% underestimation in scour and fill volumes respectively. Application of a uniform LoD based on Eq. (1) for the October 1998 minus July 1998 subtraction resulted in a 15 and 31% underestimation in scour and fill volumes, respectively; whilst for the June 1999 minus October 1998 subtraction there was a 31 and 13% underestimation in scour and fill volumes, respectively.

4.6. Aerial change detection and local topographic variability

The differences between the areas of erosion and deposition detected using the uniform error and spatially distributed error approaches are highlighted in Fig. 9. Clearly, large areas of change are not detected through use of a uniform error approach. The uniform error approach is not as sensitive at detecting morphological changes on flatter surfaces such as in bar surfaces and channel beds. To explore this further, the population distribution of local topographic variation—as determined from the σ_z grids (Fig. 4), for bar surfaces, channel beds, bank edges, and bar edges—was plotted (Fig. 10). The flatter bar surfaces and channel

Table 3
Erosion and deposition volumes calculated from DEM subtraction for the River Nent downstream instability zone for October minus July 1998 and June 1999 minus October 1998.

		Raw DEM	Uniform LoD based on D_{84} (0.2 m) (Chappell et al., 2003)	Uniform LoD LoD (Oct–Jul 98): 0.226 m LoD (Jun 99–Oct 98): 0.192 m	Spatially distributed LoD
Nent Oct 98–July 98	Deposition (m^3)	882.97	363.26	323.47	493.67
	Erosion (m^3)	997.50	478.11	436.46	581.95
Nent June 99–Oct 98	Deposition (m^3)	1381.44	795.73	812.63	930.01
	Erosion (m^3)	844.17	365.63	377.24	534.95

The table demonstrates the volumes calculated (a) using the raw DEMs, before applying an LoD; (b) after a uniform LoD based upon the D84 of the bed surface was applied; (c) after a uniform LoD using a standard deviation of error (σ_e) was applied to each surface, and (d) using the spatially distributed error approach.

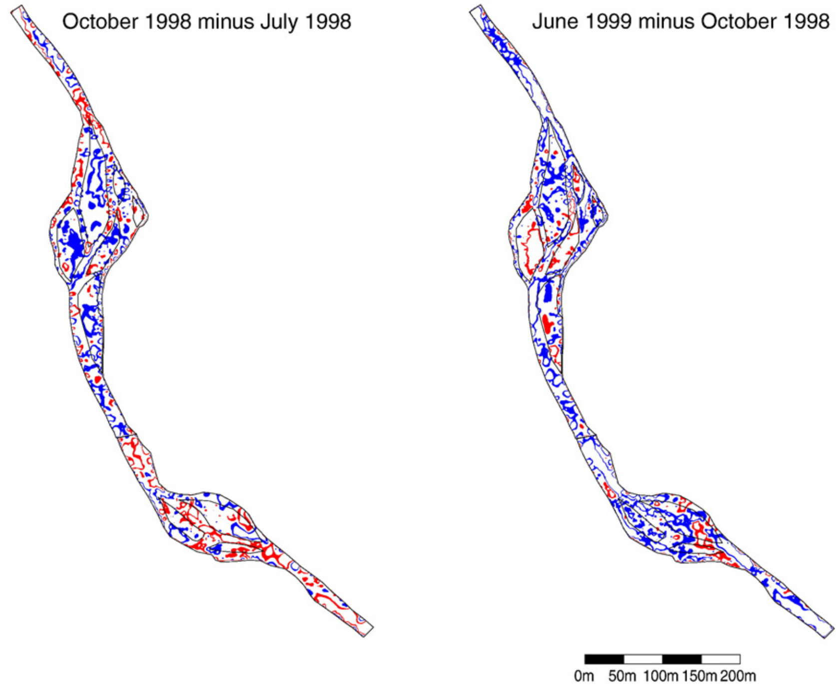

Fig. 9. Spatial distribution of additional scour (red) and fill (blue) captured through applying the spatial error filter in comparison to the uniform error filter.

beds with their low topographic variability are clearly differentiated from the bar edges and bank edges. Flatter areas found on bar surfaces and channel beds have very low local surface elevation variability with very similar median values of 0.04 m. Bar and bank edges have much greater elevation variability with median values of 0.31 and 0.44 m, respectively. Further analysis of the population distribution of areal morphological change in relation to local topographic variation is shown in Fig. 11. The spatially distributed error approach has a greater ability to capture changes over flatter surfaces such as bar surfaces and channel beds (σ_z<0.1 m, shown in blue) in comparison to the uniform error approach. Furthermore, the use of the uniform error approach is biased towards detecting change in areas of the channel with greater local surface elevation variability, such as bar and bank edges (σ_z>0.1 m, shown in yellow and stippled shading (for colour diagram please refer to web version of this article)).

5. Discussion and conclusions

The spatial extent of change in three dimensions is overestimated using DoDs created from raw survey data without error filtering, and as a consequence, such results are open to incorrect process interpretation. Many previous studies account for errors within DEMs in a uniform manner, failing to account for the spatial variability in the error. Application of uniform surface error to a DoD results in a loss of information from flatter surfaces such as bar tops. Error across these flatter surfaces is over-conservative, and hence most of the change detected is likely to be skewed toward areas with greater local topographic variability such as bar and bank edges (Fig. 11). The spatial variability in elevation errors should be taken into consideration when undertaking DEM subtraction. Spatially distributed error should be used in the determination of an appropriate LoD. This was undertaken through establishing the σ_e of elevation errors for different areas topographic roughness (σ_z). Through transformation of the σ_z grid to a σ_e grid, using the curves presented in Fig. 5B and through the application of Eq. (1) to the σ_e grid, a spatially distributed LoD grid is produced. The raw DoD may then be filtered using the spatially distributed LoD grid providing more reliable scour and fill information and aiding channel change interpretation.

In this paper we develop the Heritage et al. (2009) approach, which presents an alternative to Wheaton et al. (2009a) in the consideration of spatial error in DEMs. Both approaches can be successfully applied to any raw point cloud (*x, y,* and *z*) data collected via total station, dGPS or LiDAR. However both methods are not able to deal with DEMs that have been produced from sources such as contour lines and rasters. In this situation the accuracy of the DEM is largely governed by the resolution of the primary source (e.g. 0.5-m contour interval). We therefore recommend that where raw point clouds are available consideration is given towards the spatial error in the DEM using one of the available approaches. Studies focusing on DoD where one or both of the DEMs in the analysis has not been derived from raw point cloud data should take due caution about uncertainty and take steps to evaluate DoD uncertainty by whatever means is possible with the given dataset. However for the time being it is not possible to apply the approach presented in this paper, nor the Wheaton et al. (2009a) approach to this type of data.

The morphologic change recorded across the instability zones of the River Nent at Blagill between July 1998 and June 1999 broadly support those reported in Chappell et al. (2003). Volumetric changes using a uniform error based upon surface grain size are similar to the

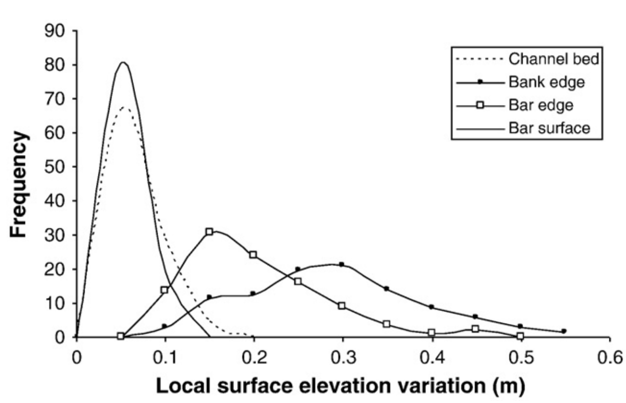

Fig. 10. Population distributions of local surface elevation variability for bar surfaces, channel bed, bar edges, and bank edges. The data used to generate the curves was extracted from the standard deviations grids (Fig. 4).

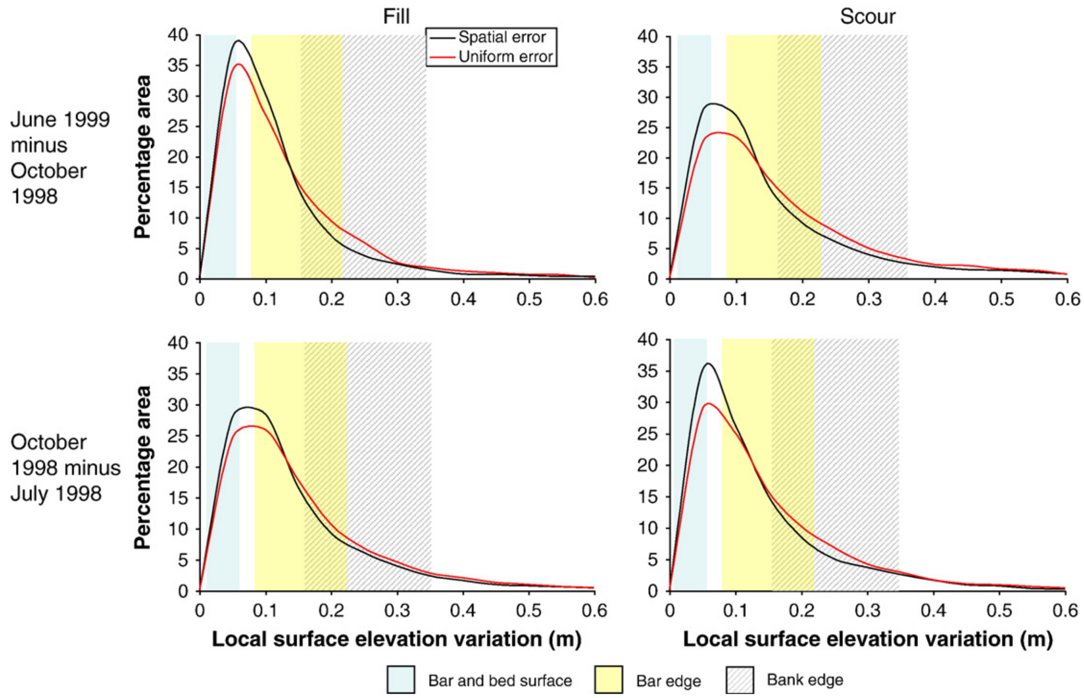

Fig. 11. Comparison of the proportional areas of scour and fill (expressed as a percentage) detected using spatial and uniform error filtering from areas with different topographic variation. Range (first standard deviation around the mean) of surface topographic variability is demonstrated for bar surfaces and channel bed (shaded in blue), bar edges (yellow), and bank edges (stippled).

volumetric changes calculated using uniform error based upon RMSE in each of the DEMs used in the DoD (Tables 2 and 3). However, more significant differences in erosion and deposition volumes are found when comparing those derived through the spatially distributed error approach with the uniform error approach derived from RMSE of the elevation errors used to produce each surface in the DEM subtraction (Eq. (1)). Spatial error filtering reveals the over-conservative nature of conventional approaches that account for a uniform error across the DEM: when the spatially variable LoD grids are subtracted from the raw DoDs, underestimates of 15 and 31% scour and fill, respectively were found for the October 1998 minus July 1998 DoD, whilst underestimates of 31 and 13% of scour and fill, respectively, were found for the June 1999 minus October 1998 DoD.

Changes captured using a uniform error are biased toward areas of the channel that have more local topographic variability such as bar and bank edges. In contrast, the use of a spatially distributed approach provides information on change from flatter surfaces such as bar tops. The new approach offers an improvement to existing protocols in so much as subtle changes, such as that which may occur on flat bar surfaces, can be captured. For fluvial geomorphology, this finding is important as subtle changes in elevation on large bar surfaces can potentially equate to large sediment volumes. This clearly has implications for the future use of DEM analysis in landform evolution monitoring throughout geomorphology.

References

Brasington, J., Rumsby, B.T., McVey, R.A., 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high-resolution GPS-based survey. Earth Surface Processes and Landforms 25, 973–990.

Brasington, J., Langham, J., Rumsby, B., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology 53, 299–316.

Brewer, P.A., Passmore, D.G., 2002. Sediment budgeting techniques in gravel-bed rivers. In: Jones, S.J., Frostick, L.E. (Eds.), Sediment flux to basins: causes, controls and consequences. : Special Publication, 191. Geological Society of London, London, UK, pp. 97–113.

Butler, J.B., Lane, S.N., Chandler, J.H., 1998. Assessment of DEM quality characterising surface roughness using close range digital photogrammetry. Photogrammetric Record 16, 271–291.

Carrara, A., Bitelli, G., Carla, R., 1997. Comparisons of techniques for generating digital terrain models from contour lines. International Journal of Geographical Information Science 11, 451–473.

Chaplot, V., Darboux, F., Bourennane, H., Leguedois, S., Silvera, N., Phachomphon, K., 2006. Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density. Geomorphology 77, 126–141.

Chappell, A., Heritage, G.L., Fuller, I.C., Large, A.R.G., Milan, D.J., 2003. Using geostatistical analysis of ground-survey elevation data to elucidate spatial and temporal river channel change. Earth Surface Processes and Landforms 28, 349–370.

Charlton, M.E., Large, A.R.G., Fuller, I.C., 2003. Application of airborne LiDAR in river environments: the river Coquet, Northumberland, UK. Earth Surface Processes and Landforms 28, 299–306.

Church, M., 1983. Pattern of instability in a wandering gravel-bed channel. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. Blackwell Scientific, Oxford, UK, pp. 169–180.

Devereux, B., Amable, G., 2009. Airborne LiDAR: instrumentation, data acquisition and handling. In: Heritage, G.L., Large, A.R.G. (Eds.), Laser Scanning for the Environmental Sciences. Wiley-Blackwell, Chichester, UK.

Fuller, I.C., Large, A.R.G., Milan, D.J., 2003. Quantifying development and sediment transfer following chute cutoff in a wandering gravel-bed river. Geomorphology 54, 307–323.

Fuller, I.C., Large, A.R.G., Heritage, G.L., Milan, D.J., Charlton, M.E., 2005. Derivation of reach-scale sediment transfers in the River Coquet, Northumberland, UK. In: Blum, M., Marriott, S., Leclair, S. (Eds.), Fluvial sedimentology VII. : International Association of Sedimentologists Special Publication, 35. Wiley-Blackwell, Chichester, UK, pp. 61–74.

Goovaerts, P., 2000. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. Journal of Hydrology 228, 113–129.

Goovaerts, P., 2001. Geostatistical modeling of uncertainty in soil science. Geoderma 103, 3–26.

Guth, P.L., 1999. Contour line ghosts in USGS level 2 DEMs. Photogrammetric Engineering and Remote Sensing 65, 229–289.

Hancock, G.R., 2006. The impact of different gridding methods on catchment geomorphology and soil erosion over long timescales using a landscape evolution model. Earth Surface Processes & Landforms 31, 1035–1050.

Heritage, G.L., Large, A.R.G., 2009. Fundamentals of laser scanning. In: Heritage, G.L., Large, A.R.G. (Eds.), Laser Scanning for the Environmental Sciences. Wiley-Blackwell, Chichester, UK.

Heritage, G.L., Milan, D.J., 2009. Terrestrial laser scanning of grain roughness in a gravel-bed river. Geomorphology 113, 4–11.

Heritage, G.L., Milan, D.J., Large, A.R.G., Fuller, I., 2009. Influence of survey strategy and interpolation model upon DEM quality. Geomorphology 112, 334–344.

Hodge, R., Brasington, J., Richards, K., 2009. Analysing laser-scanned digital terrain models of gravel bed surfaces: linking morphology to sediment transport processes and hydraulics. Sedimentology. doi:10.1111/j.1365-3091.2009.01068.x.

Holmes, K.W., Chadwick, O.A., Kyriakidis, P.C., 2000. Error in a USGS 30-meter digital elevation model and its impact on terrain modelling. Journal of Hydrology 233, 154–173.

Kastens, T., Staggenborg, S., 2002. Spatial interpolation accuracy. Kansas State Precision Conference, Great Bend. www.agmanager.info/crops/prodecon/precision/default.asp.

Lane, S.N., 1998. The use of digital terrain modelling in the understanding of dynamic river systems. In: Lane, S.N., Richards, K.S., Chandler, J.H. (Eds.), Landform Monitoring, Modelling and Analysis. Wiley, Chichester, UK, pp. 311–342.

Lane, S.N., Chandler, J.H., Richards, K.S., 1994. Developments in monitoring and modelling small-scale river bed topography. Earth Surface Processes & Landforms 19, 349–368.

Lane, S.N., Westaway, R.M., Hicks, M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surface Processes and Landforms 28, 249–271.

Lloyd, C.D., Atkinson, P.M., 2001. Assessing uncertainty in estimates with ordinary and indicator kriging. Computers and Geosciences 27, 929–937.

Milan, D.J., Hetherington, D., Heritage, G.L., 2007. Application of a 3D laser scanner in the assessment of erosion and deposition volumes in a proglacial river. Earth Surface Processes & Landforms 32, 1657–1674. doi:10.1002/esp. 1592.

Moore, I.D., Grayson, R.B., Ladson, A.R., 1991. Digital terrain modeling: a review of hydrological, geomorphological and biological applications. Hydrological Processes 5, 3–90.

Nicholas, A.P., 2003. Investigation of spatially distributed braided river flows using a two-dimensional hydraulic model. Earth Surface Processes and Landforms 28, 655–674.

Rumsby, B.T., Brasington, J., Langham, J.A., McLelland, S.J., Middeton, R., Rollinson, G., 2008. Monitoring and modelling particle and reach-scale morphological change in gravel-bed rivers: applications and challenges. Geomorphology 93, 40–54.

Siska, P.P., Hung, I.K., 2001. Papers and Proceedings of the Applied Geography Conferences. : Propagation of Errors in Spatial Analysis, 24. University of North Texas, pp. 284–290.

Vallé, B.L., Pasternack, G.B., 2006. Field mapping and digital elevation modelling of submerged and unsubmerged hydraulic jump regions in a bedrock step-pool channel. Earth Surface Processes and Landforms 31, 646–664.

Wechsler, S.P., 2000. Effect of DEM uncertainty on topographic parameters. DEM Scale and Terrain Evaluation. State University of New York College of Environmental Science and Forestry, Syracuse, New York, USA.

Wechsler, S.P., 2003. Perceptions of digital elevation model uncertainty by DEM users. URISA Journal 15, 57–64.

Weschsler, S.P., Kroll, C.N., 2006. Quantifying DEM uncertainty and its effect on topographic parameters. Photogrammetric Engineering and Remote Sensing 72, 1081–1090.

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2009a. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surface Processes and Landforms 35, 136–156. doi:10.1002/esp.1886.

Wheaton, J.M., Brasington, J., Darby, S.E., Merz, J.E., Pasternack, G.B., Sear, D.A., Vericat, D., 2009b. Linking geomorphic changes to salmonid habitat at a scale relevant to fish. Rivers Research and Applications 26, 469–486. doi:10.1002/rra.1305.

Wise, S.M., 1998. The effect of GIS interpolation errors on the use of DEMs in geomorphology. In: Lane, S.N., Richards, K.S., Chandler, J.H. (Eds.), Landform Monitoring, Modelling and Analysis. Wiley, Chichester, pp. 139–164.

Wise, S.M., 2007. Effect of differing DEM creation methods on the results from a hydrological model. Computers and Geosciences 33, 1351–1365.

Wood, J., 1996. Scale-based characterization of digital elevation models. In: Parker, D. (Ed.), Innovations in GIS 3. Taylor and Francis, London, pp. 163–175.

Wood, J.D., Fisher, P.F., 1993. Assessing interpolation accuracy in elevation models. IEEE Computer Graphics and Applications 13, 48–56.

Yue, T., Du, Z., Song, D., Gong, Y., 2007. A new method of surface modelling and its application to DEM construction. Geomorphology 91, 161–172.