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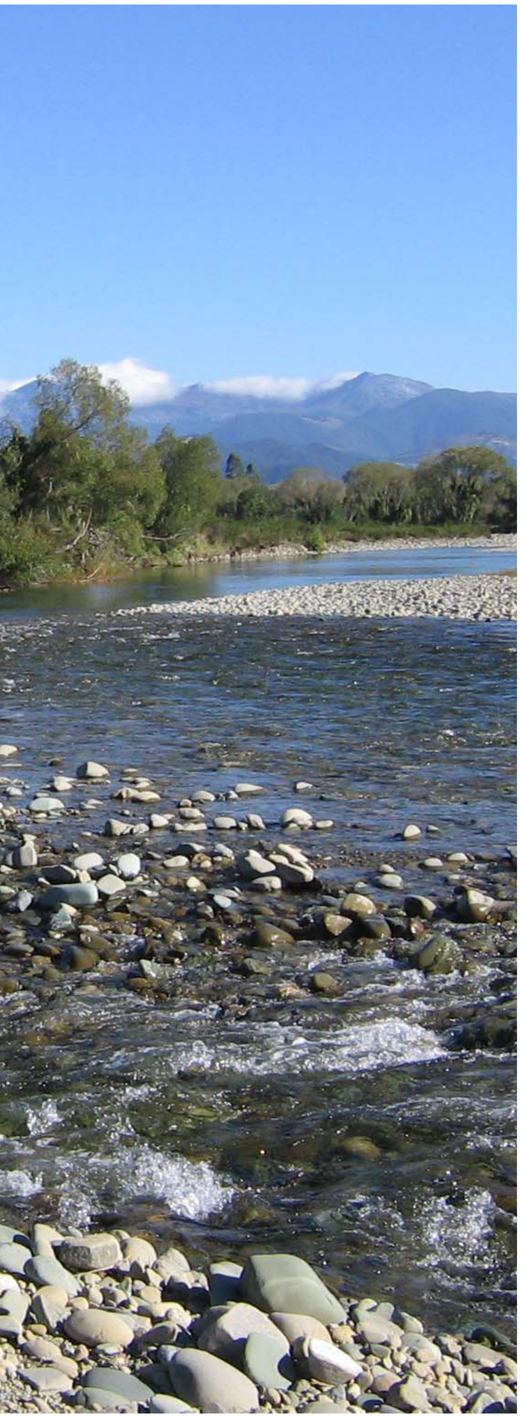

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Morphological budgeting in the Motueka River: analysis of technique

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Abstract

Morphological budgeting is a key method for monitoring and studying sediment transfers within gravelly rivers. We assess the utility of traditional cross-section approaches to budgeting using Digital Elevation Model (DEM) analysis. DEMs give a more accurate volume calculation within the constraint of sampling frequency compared with cross sections, since a greater area of river bed is sampled. DEM volume calculation within the 1.7 km 'Three Beaches' reach in the upper Motueka revealed a net loss of 3219 m^3 in this reach between 2008-2009. Comparisons of this value with cross section-based volume calculations at a range of section spacing using (i) Mean Bed Level (MBL) analysis and (ii) DEMs generated from cross section data, suggest accuracy of the budget is maximised at a critical cross section spacing not exceeding 90 m. Careful positioning of cross sections could lengthen this distance further and is essential to accurately represent river channel morphology. MBL analysis using cross-sections in the reach monumented by Tasman District Council (TDC) for river monitoring underestimates the magnitude of net sediment transfers by c. 30%.

Key words: DEM, Cross Section, Mean Bed Level, river morphology, gravel bed river

Introduction

Morphological budgeting has developed as an approach to quantifying sediment transfers based on morphological change in gravel-bed rivers (Ashmore and Church, 1998). Previous methods including direct sampling of bedload and indirect use of bedload equations (Gomez and Church, 1989) have been problematic. The morphological budget links hydraulic process and river morphology as a consequence of sediment transport, erosion and deposition. In turn, sediment transfer and channel dynamics can be measured and give information on channel stability (Church, 2006; Brewer & Passmore, 2002; Ashmore & Church, 1998).

The morphological approach has significant applications at a wide variety of temporal and spatial scales (Milan *et al*, 2007); use of time-space integration avoids complications caused by variability in the temporal and spatial bed load transport (Hubbell, 1987). The cross section technique has proved the mainstay of the morphological approach (e.g. Ashworth and Ferguson, 1986; Goff and Ashmore, 1994; Martin and Church, 1995; Paige and Hickin, 2000; Ham and Church, 2000; Brewer and

Passmore, 2002; Fuller *et al*., 2002), whereby channel cross sections are taken at various distances along a reach and repeated at fixed or variable time intervals. Comparing repeat surveys and interpolation to account for the space between the cross sections allows for volumetric calculations. Early work focused on bar scale (e.g. Neill, 1987; Ferguson and Ashworth, 1992; Ferguson *et al*., 1992; Lane *et al.*, 1994) but the approach has been extended to reach scale (e.g. Brasington *et al.*, 2000; Fuller *et al*., 2003).

Significant technical issues affect the reliability of the technique and are exacerbated at larger reach scale applications. Extrapolating changes found in a two dimensional cross section to three dimensional space assumes that the values are an adequate representation of the area between the two cross sections which puts emphasis on the position and the distance that separates two cross sections (Fuller *et al.*, 2002). Effects of downstream sedimentological structures on channel processes may be neglected due to inadequacy in the cross-section approach to express them, giving rise to high levels of uncertainties (Lane *et al*., 1994; Naden and Brayshaw, 1987; Wittenberg, 2002; Brasington *et al*. 2000). Lane *et al*., (1994) suggest that channel cross section is a legacy of hydraulic geometry and a weakness of the morphological budget approach. Furthermore, often cross-section networks may not be designed to specifically address morphological budgeting, but instead provide a snapshot of river bed level in connection with flood management.

DEMs have been used as a significant improvement to cross sectional approaches for morphological budgeting by acquisition of x,y,z coordinates via ground survey (e.g. Lane *et al*., 1994; Milne and Sear, 1997; Heritage *et al*., 1998; Brasington *et al*., 2000; Eaton and Lapointe, 2001). Fuller *et al*. (2003) were among the first to assess the difference between a cross sectional based and DEM based budget approach on a 1 km reach of the River Coquet in Northumberland. Comparisons of the cross section approach with DEM analysis showed consistent underestimating of the sediment volume loss by cross sections. In this study a net loss of 7,884 m^3 from the DEM compared to 950 m^3 from cross section analysis probably resulted from missing detecting change between cross sections due to the spacing distance and the fixed position of cross sections. DEMs were considered to be reliable: Fuller *et al.*, (2005) reported an accuracy of ± 5 cm for 96.3% of the interpolated surface of the 1 km piedmont reach of the River Coquet using the DEM approach. However, the technique was very field-intensive, thus creating difficulty if subsequent surveys are required to be within a short space of time (Brasington *et al.*, 2000). Introduction of Global Positioning System (GPS) technology resulted in a significant improvement to the total station technique of deriving a DEM in allowing topographic data to be rapidly acquired (Brasington *et al*., 2000) and at accuracies of 2 – 3 cm (Twigg, 1998; Fix and Burt, 1995; Brasington *et al*. 2000). Despite the advances in the DEM approach cross section techniques have been, and are, still used as a primary method of quantifying changes in gravel storage (Sriboonlue & Basher, 2003) due to practical difficulties associated with other techniques (Brasington *et al*., 2000). This paper focuses on morphological budgeting on the Motueka River, New Zealand using RTK-GPS to develop a DEM and compares this with the cross section approach via (a) comparison between the cross section – MBL and a cross section – DEM derived approach to quantification of gravel volumes, (b) distance between cross sections and the location of the cross section and (c) MBL analysis using TDC section lines.

Study Site

The Motueka River is situated in the north-west South Island (Figure 1) with the study reach between Kohatu and Tapawera. It drains the largest catchment (2075 km^2) in the Nelson region. The river flows for 112 km from the Red Hills. The catchment is mostly mountainous or hilly with steep river gradients; however the study site location in one of two extensive gravel deposition zones (Sriboonlue & Basher, 2003) shown in Figure 1b. The river is of interest due to river control and river improvement works as well as commercial and private gravel extraction for over 50 years resulting in considerable focus on changes in MBL and gravel storage (TDC, 2000).

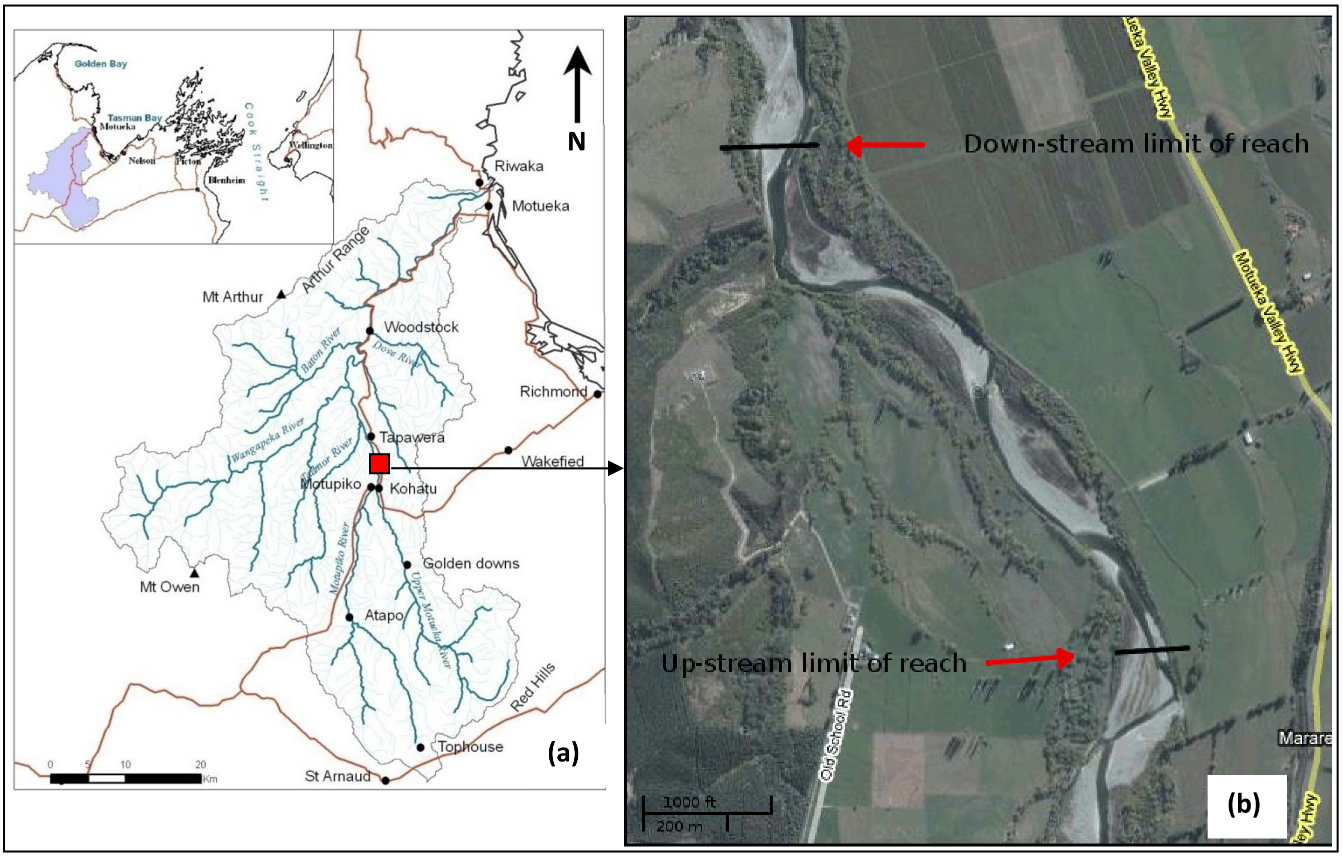

Figure 1. (a) Location of Motueka River catchment (after Sriboonlue and Basher, 2003), (b) Three Beaches Study Reach (Google Maps 2009).

Methods

Survey

A RTK-GPS system was used to obtain data using a Trimble® GPS receiver set as a base station with multiple Rover units slaved to it. Using the Rovers, coordinates of the observation points were calculated using real time algorithms and allowed rapid data acquisition with 1 second required at each observation point. Each observation had a minimum acceptable vertical accuracy of 0.05 m. Surveys were completed during autumn in both 2008 and 2009 over a 1.7 km reach of the Motueka. Points were surveyed throughout the active channel with a morphological sensitivity, such that

fewer points were sampled from broad, flat, bar platforms, while avalanche faces and riffles required higher point density. Repeat surveys were calibrated via a local monumented position and bench mark. Average point densities of 0.139 pts m^{-2} and 0.105 pts m^{-2} (Table 1) for 2008 and 2009 respectively mask higher point densities that occur around the breaks in slope.

Table 1 Survey area, points and point density for 2008 and 2009 surveys

	Area (m^2)	Points	Point Density (pts m^{-2})
2008	89881.5	12511	0.139
2009	89881.5	9424	0.105

DEMs

DEMs were generated from the surveys using Surfer®. The DEMs are based on 1 m grids but since data were sampled terrain sensitively and were not collected in grids, the DEM surface created from field data was interpolated to create the DEM. The interpolation method used Triangular Linear Interpolation (TLI) being most effective for evenly distributed data (Surfer, 2002). TLI constructs multiple irregular triangular facets based on optimal Delaunay triangulation (Lee, 1991; Tsai, 1993). All grid nodes within a triangle are defined by the triangular surface, and because the triangles are defined by original points the resulting surface is of high accuracy (Surfer, 2002; Fuller and Hutchinson, 2007).

Cross sections

Cross sectional slices at spacings of c. 30m were taken from the DEM using Surfer ® GIS for both the 2009 and 2008 surveys, extracting 57 cross sections in the reach (Figure 2). For the cross section-DEM approach each of the 57 cross sections was put into a single grid file in Surfer ® GIS to create a DEM derived from 30 m spaced cross sections. This was repeated for 60 m, 90 m, 120 m, 150 m, 180 m, 210 m, 240 m, 270 m and 300 m spacings simply by utilising the cross sections needed to create the required spacing. While it is questionable to construct a surface which has a close spacing in one direction (across the stream) and a wide spacing in the other (along the stream), this approach mimics cross-sectional budgeting and permits appraisal of the (in)accuracy of section spacing. Five DEMs were adjusted by altering the section orientation to accommodate significant channel bends, based on visual identification of a section best representing a bend to retain the general planform of the channel.

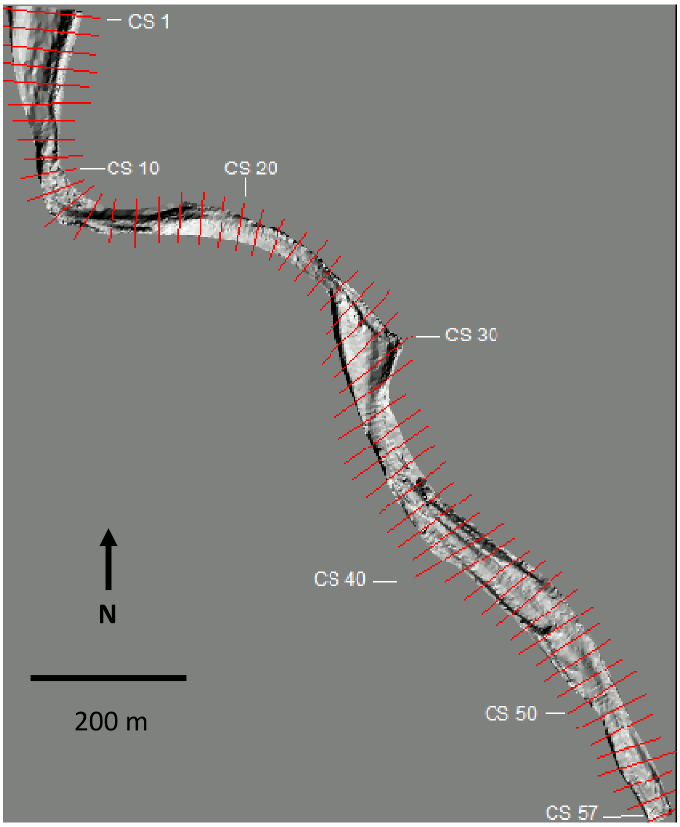

Figure 2. Active Channel DEM (2009) showing placement of cross sections

Volume calculation

1. DEM

A volume calculation was undertaken in Surfer ®, subtracting the 2008 DEM from the 2009 DEM. The same approach was applied for each of the cross section-based DEMs to derive volumes for the 30m, 60 m, 90 m, 120 m, 150 m, 180 m, 210 m, 240 m, 270 m and 300 m spaced cross section derived DEMs. The same areal extents were used for each year. Surfer ® uses three numerical algorithms for volume computation: Trapezoidal, Simpsons, and Simpsons 3/8 rule (Surfer 2002).

2. MBL

The MBL approach to calculate volume was undertaken using the method after Sriboonlue & Basher (2003). The 2008 and 2009 cross sections were extrapolated beyond the end points to give the same distance of the Active Channel width (ACW) for each year. This was done intuitively to give the mostly likely continuation of the slope. In most cases the 2009 data were simply merged with the 2008 data to provide the most conservative change. This is appropriate as extrapolation was mostly needed across stable banks and vegetated bars where change was negligible. Furthermore extents of extrapolations were only across short distances, with insignificant effects on calculations. The change in distance between each adjacent data point across the cross section and the average elevation of two adjacent data points were multiplied together to give the area between two adjacent data points (Equation 1).

$$A = \left(\frac{Elev_1 + Elev_2}{2}\right) \times (Dist_2 - Dist_1) \qquad \text{Equation 1}$$

This process was repeated along the entire distance of the cross section. The resulting areas were summed to give the total area of the cross section. Subtracting the 2008 total area from the 2009 total area gave the net change in cross sectional area for an individual cross section which was either positive or negative.

The distance between each cross section was accurately calculated from the mid-point of each cross section. Northings and Eastings were each averaged to give mid-point coordinates. Subtracting two adjacent Northings and Eastings coordinates gave difference in Northings and difference in Eastings. Pythagoras was used on these values to calculate the difference in distance as shown in Equation 2.

$$Distance = \sqrt{[(Northings_1 - Northings_2)^2 + (Eastings_1 - Eastings_2)^2]} \qquad \text{Equation 2}$$

The difference in area of two adjacent cross sections was averaged to give an average area of difference for the section. The distance between the adjacent cross sections was multiplied by the average difference in area. This was repeated for each adjacent set of cross sections, the sum of which was the total change in volume. This is represented in Equation 3.

$$\delta V = \frac{(\delta A_1 + \delta A_2)}{2} \times (Dist_1 - Dist_2) \qquad \text{Equation 3}$$

In addition, the section lines used by Tasman District Council in their five-yearly river surveys were also compared with the values obtained in this study where the MBL method is used to derive a net

volume change for the reach as a stand-in TDC value. Cross sections 28, 40 and 54 in this study are the same cross sections as 17, 17a and 18 used in the TDC 'upper Motueka' survey (Sriboonlue & Basher, 2003) and cross section 1 is used as a surrogate to TDC cross section 16 which lies just outside of the reach studied. The actual MBL is calculated for these cross sections as a comparison to those displayed by TDC and calculated via Equation 4 where *A* is the cross sectional area and ACW is the Active Channel Width.

$$MBL = \frac{A}{ACW} \quad \text{Equation 4}$$

3. Accuracy

Accuracy of the interpolated data in DEM analysis was obtained using a standard error calculation (Equation 5) where $SE_{\bar{x}}$ is standard error of the mean, *s* is the sample standard deviation and *n* is the sample size.

$$SE_{\bar{x}} = \frac{s}{\sqrt{n}} \quad \text{Equation 5}$$

The 2008 and 2009 elevation values have a vertical accuracy of 0.024 m and 0.025 m respectively (Table 2) and shows half the standard accuracy to the minimum allowed during data acquisition. In construction of the cross-section derived DEMs for the respective spacings however, there is an increase in the standard error of the points. This is a simple relationship to the number of values used which decreases as the cross section spacing increases. As a result the standard error becomes higher than the minimum acceptable error of the GPS at 0.05 m where the highest errors for the 300 m cross sections are 0.1 m to 0.109 m (Table 2).

The accuracy of the generated DEMs is explored using the error standard deviation (*S*) (Equation 6) and Mean Error (ME)(Equation 7) (Fisher & Tate, 2006; Fuller & Hutchinson, 2007) which provides an estimate of the error based on original data points compared to the DEM values. This provides an estimate of the overall DEM quality only which is not necessarily unbiased (Fuller & Hutchinson, 2007). Fuller *et al*. (2003) found differences of 0.02 m and 0.05 m at best between interpolated and independently surveyed data. The method is used as opposed to the root mean square error which assumes that the mean error is zero. However, mean error is often not zero due to surface under or overestimation in DEM construction.

$$S = \sqrt{\frac{\Sigma[(z_{\mathrm{DEM}} - z_{\mathrm{ref}}) - ME]^2}{n-1}} \quad \text{Equation 6}$$

Where z_{DEM} is the DEM elevation, z_{ref} is the original point elevation, ME is the mean error (Equation 7) and *n* is the sample number.

$$ME = \frac{\Sigma\big((z_{\mathrm{DEM}} - z_{\mathrm{ref}})\big)}{n} \quad \text{Equation 7}$$

The value of ($z_{\mathrm{DEM}} - z_{\mathrm{ref}}$) was calculated using the residual function on Surfer ® GIS (Equation 8) whereby

$$z_{res} = z_{dat} - z_{grd} \quad \text{Equation 8}$$

Where z_{res} is the residual value, z_{dat} is the elevation value in the DEM data file and z_{grd} is the elevation from the original data values. Table 2 displays the S and ME values.

Table 2 Accuracy of DEMs

DEM	Vertical accuracy	TLI Residual (m)		Error Standard Deviation (S)	Mean Error
	m	min	max		
2008 true	0.0242	-0.804	0.617	0.0590	-3.56E-03
2009 true	0.0253	-1.271	0.674	0.0588	-2.56E-03
2008 30m	0.0363	-0.063	0.054	0.0072	-3.4E-04
2009 30m	0.0372	-0.070	0.051	0.0068	-3.1E-04
2008 60m	0.0509	-0.081	0.090	0.0080	-1.6E-04
2009 60m	0.0528	-0.118	0.053	0.0075	-8.6E-05
2008 90m	0.0633	-0.082	0.055	0.0078	2.6E-04
2009 90m	0.0645	-0.273	0.055	0.0112	1.13E-04
2008 120m	0.0725	-0.044	0.059	0.0074	6.44E-04
2009 120m	0.0752	-0.062	0.129	0.0092	3.5E-04
2008 120m adj*	0.0724	-0.044	0.059	0.0074	5.76E-04
2009 120m adj*	0.0745	-0.118	0.085	0.0089	1.21E-04
2008 150m	0.0822	-0.079	0.107	0.0093	9.21E-04
2009 150m	0.0833	-0.044	0.071	0.0069	5.81E-04
2008 180m	0.0898	-0.039	0.077	0.0091	2.67E-04
2009 180m	0.0915	-0.103	0.062	0.0109	6.13E-05
2008 180m adj*	0.0893	-0.040	0.060	0.0090	2.69E-04
2009 180m adj*	0.0902	-0.061	0.045	0.0088	2.6E-04
2008 210m	0.0942	-0.034	0.055	0.0078	1.342E-03
2009 210m	0.0968	-0.040	0.053	0.0070	6.54E-04
2008 210m adj*	0.0922	-0.050	0.055	0.0084	1.338E-03
2009 210m adj*	0.0932	-0.040	0.053	0.0082	9.85E-04
2008 240m	0.1081	-0.044	0.152	0.0104	7.34E-04
2009 240m	0.1140	-0.127	0.302	0.0228	1.254E-03
2008 240m adj*	0.1035	-0.047	0.056	0.0087	8.79E-04
2009 240m adj*	0.1068	-0.064	0.062	0.0090	7.79E-04
2008 270m	0.1076	-0.080	0.165	0.0177	2.264E-03
2009 270m	0.1045	-0.195	0.134	0.0213	1.556E-03
2008 300m	0.1029	-0.084	0.118	0.0123	1.483E-03
2009 300m	0.1091	-0.042	0.090	0.0110	1.978E-03
2008 300m adj*	0.1006	-0.042	0.063	0.0106	1.785E-03
2009 300m adj*	0.1027	-0.088	0.043	0.0101	6.85E-04

*Adj = adjusted cross sections

The true DEM and the 30 m and 60 m derived DEMs for both 2008 and 2009 show a negative *ME*, which indicates that the DEM lies slightly lower than the real values. This pattern reverses for the remaining DEMs showing a positive bias. Each DEM type has the same bias for both the 2008 and 2009 survey; combined with similar orders of magnitude, the accuracy is upheld. Fuller & Hutchinson (2007) indicated through error maps that the spatial distribution of the errors was located around areas of greatest topographic change such as cut banks showing that despite increased point density in these areas the interpolation method still has difficulty. This may be due to the Gibbs phenomenon where error is a result of the model over or underestimating where there are slope discontinuities (Florinsky, 2002). Similar error distributions to Fuller & Hutchinson (2007) were found for the 2008 and 2009 true DEMs at Motueka River (Figure 3). Fuller *et al*. (2003) suggest that close correspondence between the cross section and DEM values was not necessarily expected due to the propagation of measurement errors due to surface roughness (e.g. pole placement relative to the clasts), thus a repeat survey on the same day would not necessarily have a close correspondence.

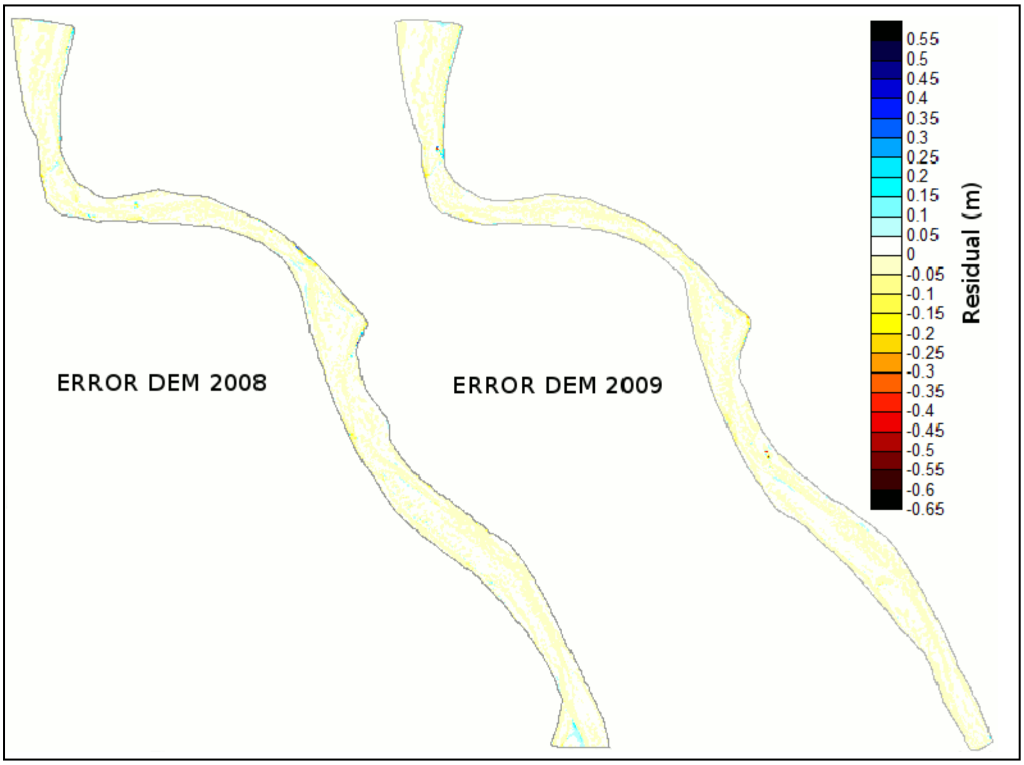

Figure 3 DEM showing error distributions using residual analysis

Results

The true DEM of difference (Figure 4) shows a net loss of -3219.46 m^3 (Table 3) when averaged between the three methods for volume calculation. The three rules give very similar results with a standard deviation of 3.049 m^3; close agreement between the three methods indicates appropriate grid resolution (Fuller *et al.*, 2005). Errors for the volume calculation can be inferred from the vertical accuracy of the DEM elevation (Table 2). Fuller & Hutchinson (2007) show that error associated with scour and fill calculation using Kriging data normally range between 3 % and 8 %, and that TLI volume accuracy is likely to be accurate to ± 5%.

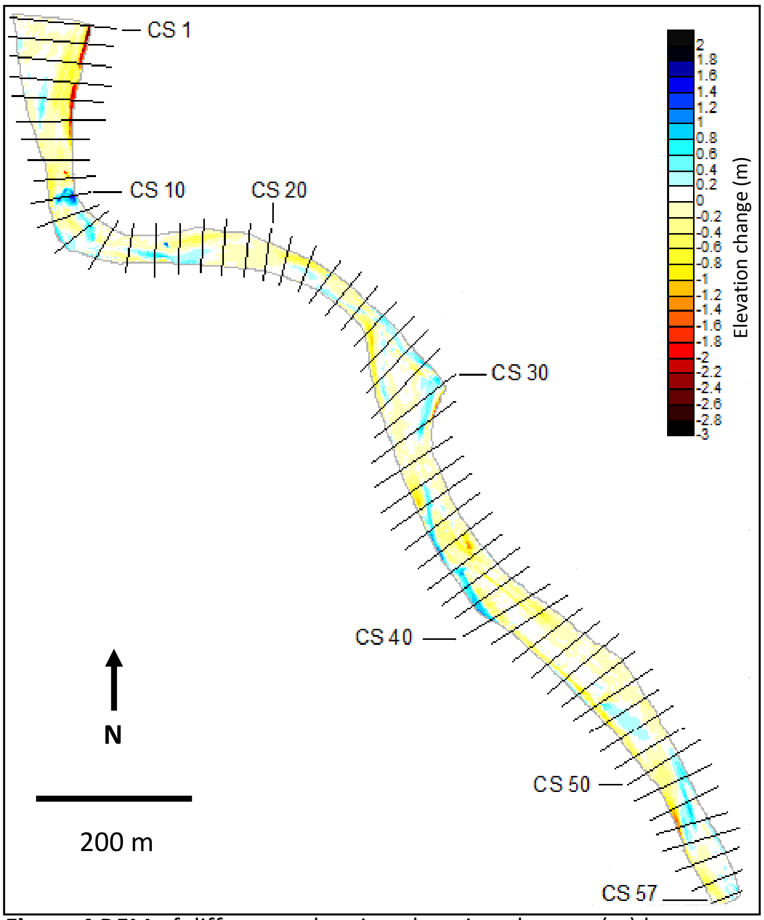

Figure 4 DEM of difference showing elevation changes (m) between 2008 and 2009 with all cross sections overlaid.

Table 3 Volume calculations

Type	Trapezoidal Rule	Simpson's Rule	Simpson's 3/8 Rule	DEM Average	MBL derived
True DEM	-3218.89	-3222.75	-3216.74	-3219.46	
30m	-2758.45	-2762.33	-2760.33	-2760.37	-3204.09
60m	-3204.90	-3198.45	-3209.49	-3204.28	-3879.63
90m	-683.64	-683.83	-682.90	-683.456	-598.28
120m	-3660.78	-3645.94	-3658.77	-3655.16	-6778.37
120m adj*	-3891.09	-3868.05	-3893.82	-3884.32	-5418.22
150m	-5136.62	-5130.73	-5137.01	-5134.79	-6966.46
180m	-2887.56	-2884.09	-2884.09	-2885.25	-2351.39
180m adj*	-2507.94	-2506.73	-2506.68	-2507.11	-528.15
210m	-3416.08	-3418.63	-3416.00	-3416.91	-3241.77
210m adj*	-501.602	-492.85	-501.63	-498.692	-389.17
240m	-4375.20	-4376.37	-4374.34	-4375.3	-8231.74
240m adj*	-3750.61	-3749.65	-3750.93	-3750.39	-3214.09
270m	1145.68	1148.65	1143.61	1145.982	1219.70
300m	-3460.56	-3455.88	-3456.59	-3457.68	-3556.67
300m adj*	2758.13	2762.08	2758.97	2759.729	1718.35

*Adj = adjusted cross sections

Volumes calculated from the MBL approach and the cross-section derived DEM approach are shown in Table 3 and illustrated in Figure 5 and an additional ratio is shown in Figure 6. Both cross-section derived DEMs and MBL show similar patterns in relation to the cross section spacing. Two DEMs show an opposite trend of a positive volume (negative ratio), 270 m and 300 m adj. The 90m, 210 m adj as well as the MBL 210 m adj show significantly less volume loss.

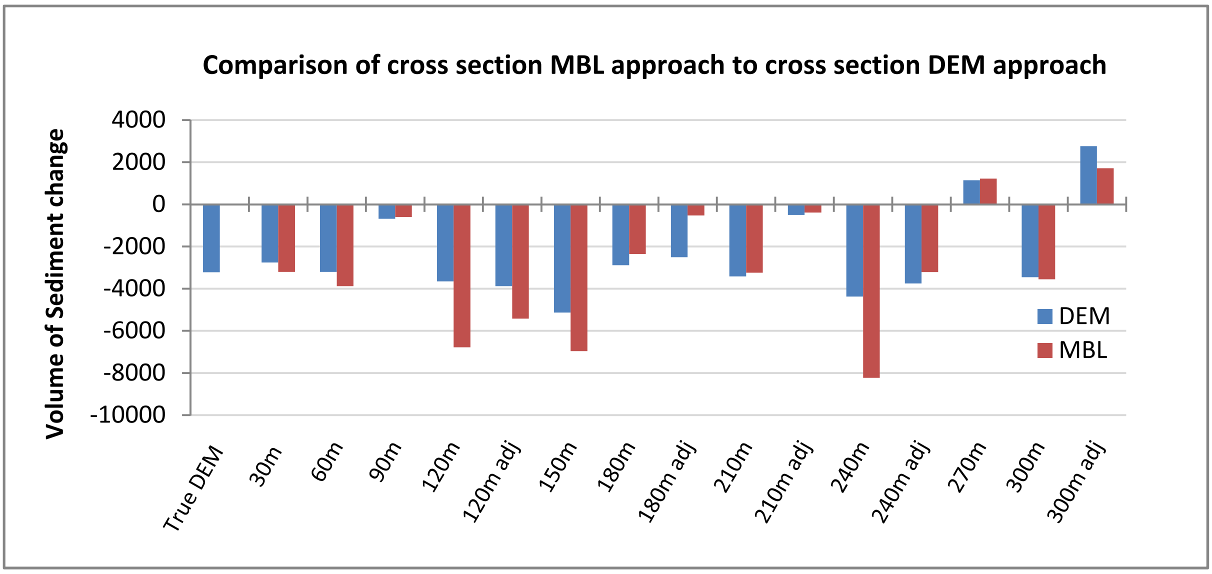

Figure 5 Graph of Net volumes (m^3) comparing MBL and DEM derived values

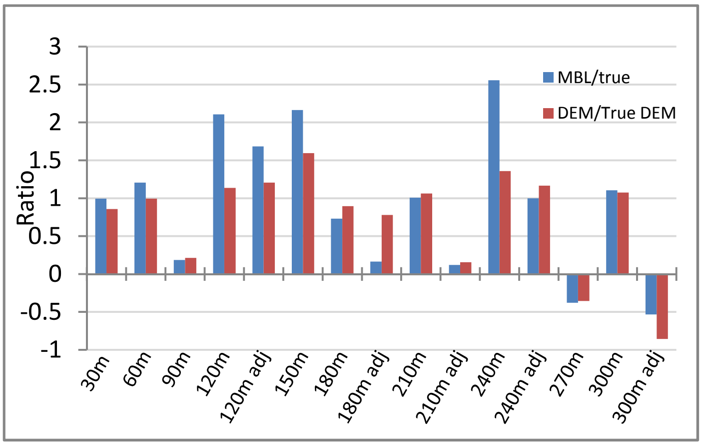

Figure 6. Ratio of MBL and cross-section derived DEM approaches to the True DEM for successive cross sections.

Comparison of MBL values with cross-section derived DEMs is considered further via difference in values (Figure 7) and a ratio of the MBL to DEM (Figure 8). Five MBL volumes, the 120 m, 120 m adj, 150 m, 240 m and the 300 m adj show significant (more than 1000) difference of volume loss compared with the respective DEMs. All of these except the 300 m adj show an exaggeration of negative volume. The ratio of MBL to cross-section derived DEM shows largest differences independent of the volume quantity. The 180 m adj shows the largest difference with a ratio of 0.25 due to the very small MBL volume that was calculated in comparison to the DEM. The same four volumes that vertically exaggerated the net volume loss show a higher ratio here too, between 1.35 and 1.85

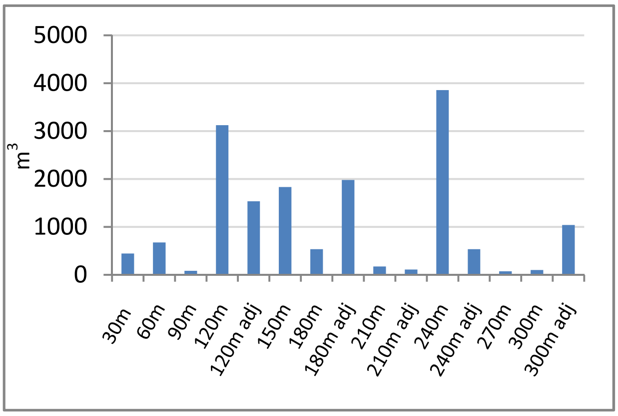

Figure 7. Difference between MBL and cross-section derived DEM volumes for successive cross sections

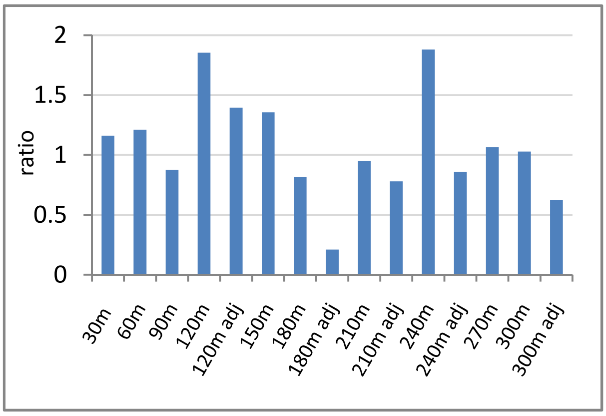

Figure 8. Ratio of MBL to cross section derived DEM volumes

Figure 9 shows spatial distributions of erosion and deposition for each DEM of difference constructed from cross-section data. The effect of the cross section spacing can be seen with the volume change for one location being stretched longitudinally along the reach e.g. the 270 m and 300 m adjusted DEM of difference have a higher degree of aggradation (blue) shown in (m) and (n) of Figure 9, as a result of the cross sections that were used. In effect the cross sections have a smoothing affect on the morphological units of the reach. The shape of the active channel loses true form with the wider spaced cross sections which is why the adjusted DEMs were formed to take account of the important bends which determine the planform of the channel.

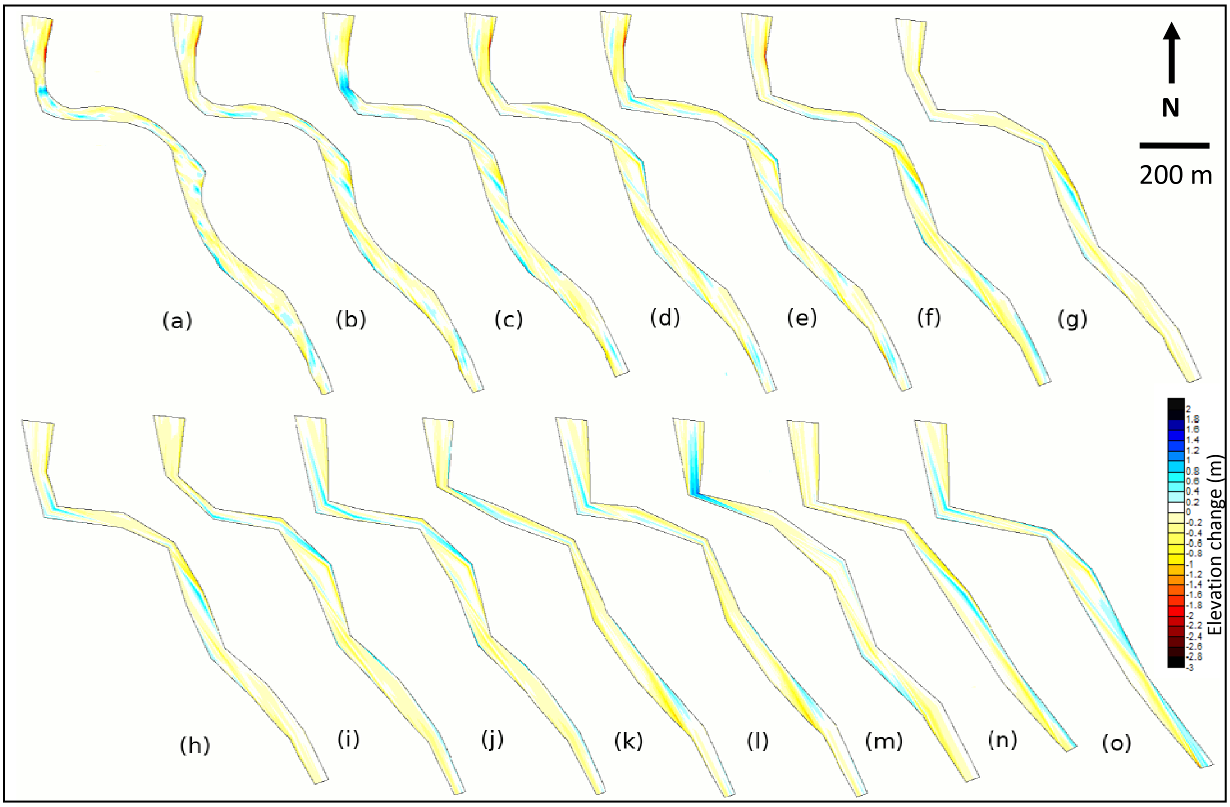

Figure 9 DEMs of difference: (a) 30 m; (b) 60 m; (c) 90 m; (d) 120m; (e) 120 m adj; (f) 150 m; (g) 180 m; (h) 180 m adj; (i) 210 m; (j) 210 m adj; (k) 240 m; (l) 240 m adj; (m) 270 m; (n) 300 m; (o) 300 m adj. Elevation changes in metres.

The three cross sections in the Three Beaches reach which form part of TDC's river monitoring network were also used to generate a morphological budget based on MBL (Table 4). This utilises the standard procedure used by TDC to assess change in gravel volumes in the river. The reach net change using this procedure generates a volume substantially lower than the true DEM, but within the range of volumes generated from cross-sections (Table 3).

Table 4. MBL and volume changes based on TDC section lines

Cross section No/ TDC Number	**MBL (m)**		**Change in MBL (m/yr)**	**Volume (m^3)**
	2008	**2009**		
CS 28/ 17	165.96	165.99	-0.0260	-4212.15
CS 40/ 17a	167.82	167.88	-0.0587	1227.35
CS54/ 18	169.51	169.49	0.0174	770.93
Reach net				**-2213.87**

Discussion

The results show that the two volume calculations which differed most from the true DEM value of sediment transfer were derived from the two largest spaced cross sections (270 m and 300 m adj). It

is however invalid to say that cross sections spaced more than 270 m apart become notably inaccurate since the 300 m spaced cross section that was not adjusted yielded a volume which differed by only 30 m^3 from the volume calculated from the true DEM. This also brings into question the need for such adjustment. Suffice to say however that with increasing cross section spacing, the probability of inaccurate volume calculations increases. This is shown by the 30 m and 60 m spaced cross sections where the comparison with the true DEM yields similar net changes. The DEM of difference for 30 m and 60 m (Figure 9, (a) and (b)) retain much of the detail possessed in the true DEM (Figure 4). Distances beyond that of 60 m start to become less reliable and results suggest a possible critical distance between 60 m and 90 m, dependent on the size of the morphological units for the reach.

However an important factor is the positioning of the cross sections and how accurately they represent the riverbed at each location for the morphological unit it bisects (Fuller *et al.*, 2002; Lane *et al.*, 1994; Naden & Brayshaw, 1987; Wittenberg, 2002; Brasington *et al.* 2000; Noell, 1992; Christensen, 2001). This particular issue is shown by the 90 m calculation as well as each of the adjusted cross sections. The true DEM shows a localised area of deposition which occurs towards the north end of the reach which cross section 10 bisects (Figure 10). The 90 m and the 270 m adj both enhance this localised deposition significantly altering the net volume change which is shown in (c) and (m) of Figure 9 where the blue aggradation is spread longitudinally.

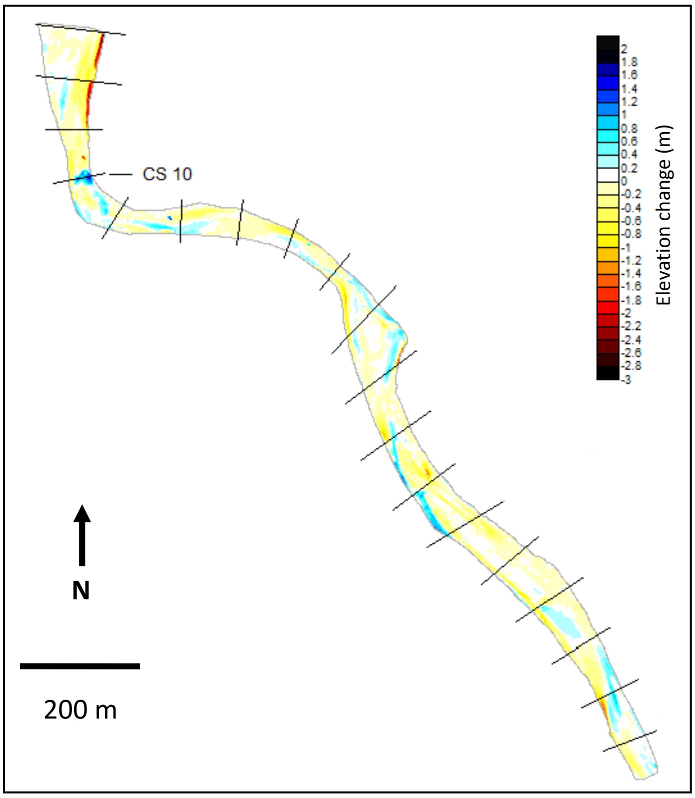

Figure 10. 90 m cross sections overlaid on the true DEM elevation changes (m)

Figure 11 shows the cross section locations of the 300 m DEM of difference (a) and the adjusted 300 m DEM of difference (b) where it is not immediately apparent why the dramatic difference in net volume changes for the two 300 m DEMs occurs (Table 3). However, the cross sectional area changes for the 300 m spacings (Table 5) make the differences immediately apparent. Using cross section 12 instead of cross section 11 alters the area by 15.21 m^2. When this is averaged with the adjacent cross sections for the volume calculation, a large area of the reach is affected; cross section 1 is effectively cancelled out, and cross section 23 is enhanced dramatically. This demonstrates the significance of cross section positioning on quantification of sediment budgets using this approach.

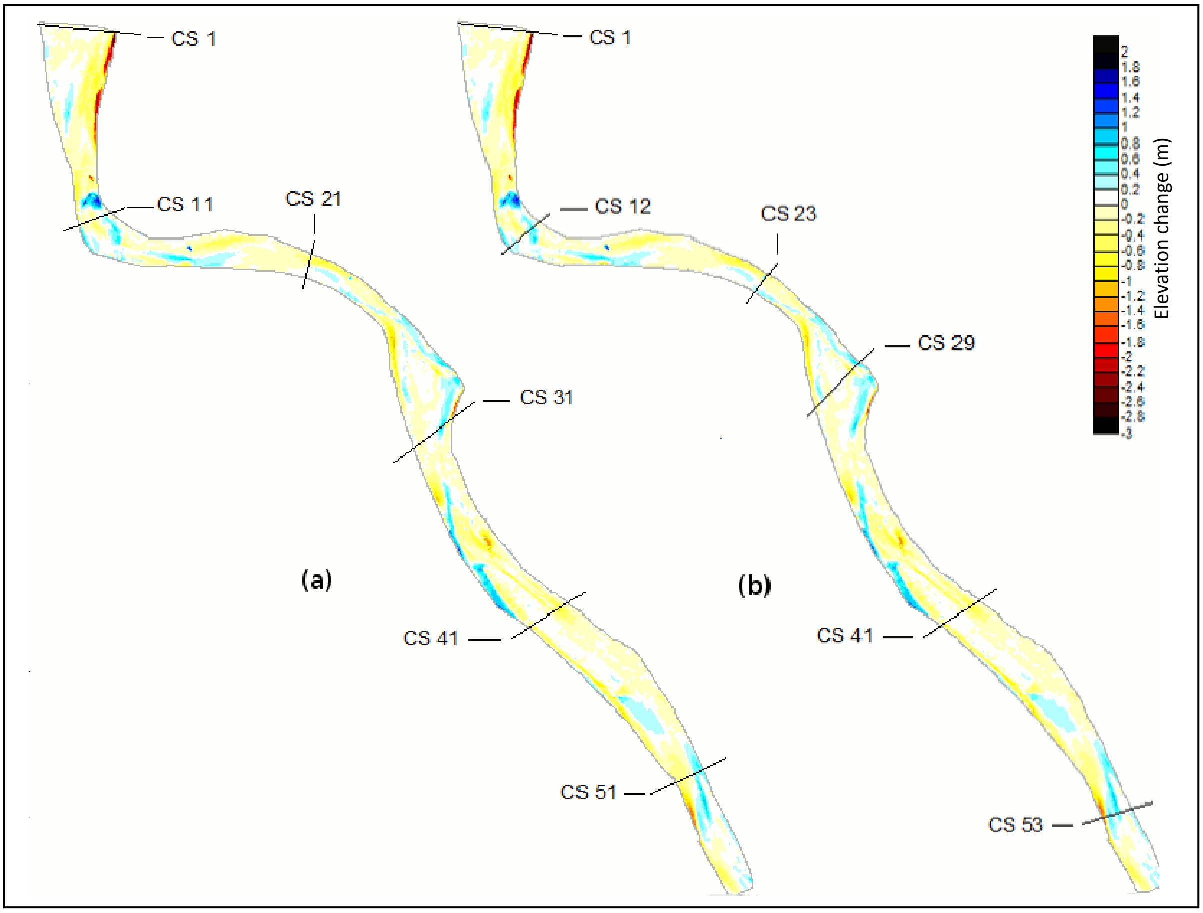

Figure 12. (a) 300 m and (b) 300 m adj cross section positions overlaid on true DEM elevation changes (m)

Table 5. Change in area for cross sections in 300 m and 300 m adj calculations

	300 m		**300 m adj**
	Change in area (m^2)		**Change in area (m^2)**
CS1	-12.60	**CS1**	-12.60
CS11	-2.21	**CS12**	13.00
CS21	-3.98	**CS23**	4.31
CS31	5.79	**CS29**	0.63
CS41	-5.40	**CS41**	-5.40
CS51	-1.32	**CS53**	0.57
Volume change	-3556.67 m^3		1718.35 m^3

Any localised erosion or deposition may be missed or enhanced by extrapolating changes observed between cross-sections, be they for the purpose of deriving MBLs or DEMs. It is the relative balance between erosion and deposition which results in the net volume change, thus if proportionally equal volumes of erosion and deposition are missed or recorded then the net change will remain unchanged, hence the cross sections may or may not adequately reflect sediment transfers within the reach, depending upon their placement. This is illustrated by the 300 m spaced cross section which has a similar value to that of the true DEM, analysis of the DEM of difference (Figure 9(n)) shows that it is devoid of significant areas of both deposition and aggradation. It may not be limited to localised erosion or deposition; the 210 m shows c.3000 m^3 additional net volume loss (Table 3)

than the 210 m adj. The DEM of difference (Figure 9) does not appear to show any prominent visual difference. The difference may arise from a more spatially extensive, but shallower pattern of deposition as noted by Fuller *et al*. (2003). The adjustment of one cross section may have added a shallow extensive aggradation pattern to the 210 m adj DEM, particularly when the vertical accuracy decreases for the more widely spaced cross sections (Table 2). It should be noted that the critical distance mentioned above would be affected by cross section placement, thus the possibility exists that the 90 m spacing may simply reflect fortuitous placement of cross sections. However, as the spacing increases, the likelihood of misrepresenting channel morphology between sections has the potential to increase.

Figure 5 shows that morphological budgeting using a cross section-generated DEM-based approach tends to show more conservative estimates of sediment transfers compared with MBL values. This probably reflects the interpolation effects during DEM generation where values of two adjacent cross sections would be more accurately merged into each other, taking account of the topography. The MBL approach however would only account for this factor to a certain extent, having an averaged value between adjacent cross section that is linearly applied to the section is limiting (Sriboonlue & Basher, 2003). An approach using DEMs generated by cross section data may therefore yield more accurate results in relation to a true DEM as opposed to the MBL approach. However, the results are not consistent (Figures 6-8) and it is debatable whether MBL is particularly less accurate than deriving DEMs from the same cross sections. What is clear is that both the cross section derived DEM and the cross section generated MBL methods are not as comprehensive as the true DEM.

However, much monitoring of bed levels and morphological budgeting at a management level is focused around cross sections due to availability of resources, time and financial restraints as well as manpower. Creating a high resolution DEM is resource demanding. Multiple GPS gear is needed for efficient surveys, as well as people to man them. Nevertheless regional councils need to be able to monitor large scale reaches in an efficient yet accurate manner. Typically, reaches are monitored using c. 500 m cross section spacing. The sections at Three Beaches used by TDC generated a net volume change of -2213.87 m^3 (Table 4) for the 2008-2009 period, which suggests a significant (c. 30%) underestimation of the sediment transfers taking place in the reach (3219.46 m^3, cf Table 3). However, it is also acknowledged that a complete point derived DEM of the area is not viable for large scales. The results here indicate that 60 m cross sections would provide data at a level of accuracy consistent with a complete point DEM approach at this site. The use of RTK-GPS to acquire the data as opposed to a Total Station, also provides a means of rapid data acquisition (Brasington *et al*., 2000; Higgitt & Warburton, 1999).

Conclusion

This paper has attempted to use a 1 m resolution DEM derived from c.10 000 data points in the Three Beaches reach of the Motueka River to evaluate (a) cross sectional-MBL and cross section-DEM approaches to quantifying net volume changes in gravel storage; (b) cross section spacing

accuracy and the effect of location; (c) volumes generated by conventional MBL approaches using TDC survey lines within the reach:

(a) The cross-section DEM approach appears to reveal more accurate estimates of sediment transfer as the MBL approach tends to over-estimate some volumes. However the differences are not consistent and the results in fact suggest a degree of consistency between these approaches in assessing sediment transfer volumes.
(b) The probability of error associated with cross-section derived sediment budgets, be they MBL or used to generate DEM-based budgets, increases with wider section spacing. Nevertheless, widely spaced cross sections could still yield surprisingly accurate results, but with much less certainty. The more important factor to be considered is the location of the cross section and how well it represents the reach or morphological unit it bisects. This is important when cross sections bisect localised areas of erosion or deposition, which may then be extrapolated across the reach segment it is deemed to represent. Critical spacing not exceeding 60 m to 90 m offers the best confidence in accuracy of volumes computed.
(c) Sediment transfers calculated using TDC section lines underestimate volumes derived from whole-reach DEM by c. 30%. This suggests that the current location of TDC monitoring sites is probably grossly underestimating sediment transfers in this reach. Whether this is consistently the case in adjacent reaches is the subject of ongoing research.

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