Development of digital photogrammetry for automated monitoring of large gravel-bed rivers

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Abstract

High-resolution monitoring of the topography of braided gravel riverbeds is becoming increasingly important for river management and research. Conventional ground survey techniques become impractical at order 1 km width scale, which is typical of many braided rivers on the Canterbury Plains, New Zealand. Digital photogrammetry provides an automated method to generate digital elevation models (DEMs) of large areas at high point densities, and so offers a potential tool for cost-effective surveys of dry areas of braided riverbed. This paper describes and tests an automated procedure for using digital photogrammetry to extract topography from both exposed areas of river bed and from relatively shallow channels containing clear water, thus allowing a DEM to be produced for the whole riverbed.

Keywords: *Digital photogrammetry, braided rivers, Ashburton River, water depth*

1 Introduction

Surveys of riverbed topography are key requirements for effective river management. Monitoring bed levels and bank position identifies trends of lateral migration, aggradation, and degradation, which forewarn of problems such as bank erosion, bridge-pier scour, and reduced flood conveyance. Riverbed surveys are also used to compute budgets of bed material, required for managing gravel extraction. Given adequate detail, they can also be used to monitor bedload movement by linking "sources" (erosion sites) with downstream "sinks" (deposition sites) and to define the boundaries for numerical models which are used to predict flood levels, sediment transport, and relationships between habitat quality and water discharge. The traditional monitoring approach for New Zealand's riverbeds has been to establish a network of cross-sections which are periodically resurveyed. Typically, however, section spacing and frequency of re-surveying tend to be constrained by practical issues and cost, rather than being designed on a rational basis that relates section spacing to the uncertainty in the result.

Digital photogrammetry is an approach that may provide a cheaper, more efficient, and more accurate method of monitoring riverbed morphology. A principal limitation is that it only provides information on exposed areas of riverbed [1], although this is minimised for the case of wide braided rivers, such as occur on the Canterbury Plains, because for much of the time only a small proportion of their beds are wetted [2]. Nonetheless, the wetted areas still require special treatment. Field surveying at low discharge is an expensive solution. There are two alternative approaches that are image-based. First, if the water is clear, so that the submerged bed can be 'seen', through-water photogrammetry may theoretically be used, and a basic correction for the real versus apparent depth included by appropriate refraction modelling. Second, if the water is turbid, depth information may be acquired by image classification techniques, although this requires some empirical calibration with data obtained by ground survey. In this paper we describe an automated technique for extracting bed topography data from relatively shallow, clear-water channels based on through-water digital photogrammetry, and test it with independent data from a braided riverbed.

2 Basic principles of digital photogrammetry

Digital photogrammetry allows automated extraction of topographic data from overlapping digital imagery (e.g., air-photographs scanned into a digital format). It stems from traditional photogrammetric methods that are based upon the special relationship that exists between points on the ground surface (the object space) and their position on images of that surface (the image space). The form of this relationship is a function of the position and orientation of the camera used to acquire the imagery, and properties of the camera lens and media used to store the imagery. Once the form of this relationship is known, and with two images of the same area taken from different positions so as to meet certain geometrical requirements (a stereo-pair), the position of a point that appears on both images is measured, and this will be sufficient to estimate the actual ground coordinates of that point.

The analytical photogrammetric approach, which became popular from the 1970s, treats the relationship between object space and image space mathematically. It requires expensive hardware and, because individual points need to be manually digitised, is relatively slow. A recent major development of the analytical approach has involved replacing manual digitisation with automated stereo-matching. In the simplest terms, this involves analysis of digital data by identifying a point (i.e., a pixel) on one image and then trying to find the corresponding point on the second image by comparing the properties of surrounding pixels. Whilst attention has to be given to getting the imagery into digital form (for instance, aerial photographs should be scanned using a photogrammetric-standard scanner from either negatives or diapositives), and many of the traditional controls on photogrammetric data quality remain (such as having an adequate camera calibration and sufficient ground control to recover the position and orientation of the camera when the images were acquired), the increased speed and reduced cost have allowed digital photogrammetry to be used much more widely for morphological monitoring.

3 Approach for clear-water channels

If the water is clear and not too deep (a common situation in gravel-bed rivers at low flows), and the photography can 'see' the river bed, then accurate through-water photogrammetry is theoretically possible. Light passing through an air-water interface is refracted according to Snell's law:

$$n = \frac{\sin i}{\sin r} = \frac{R}{D} \tag{1}$$

where n is the refractive index of water, i is the angle of an incident ray of light at the water surface, r is the angle of the refracted ray of light below the water surface, R is the actual water depth, and D is the apparent water depth. The degree of refraction in clear water can be accurately calculated and has been shown to be remarkably constant ($n = 1.340 \pm 0.007$) for temperatures between 0 and 30° C [3]. The approach developed in this paper is similar to that used by Fryer [4], and is based on the premise that, given estimates of D derived from digital photogrammetric output, it is possible to derive estimates of R and hence correct the original photogrammetric estimates of bed elevation.

The correction procedure proceeds through seven steps. (i) An initial photogrammetrically-acquired Digital Elevation Model (DEM) is used to correct the original image for distortion effects to produce an orthophoto. (ii) Non-directional edge detection of the orthophoto is then used to produce a map of water edges, and a minimum distance classification of the orthophoto is used to produce a binary classification of wet and dry areas. (iii) Where the binary classification identifies wet locations, estimates of water elevation are interpolated from the waters edge map using kriging. (iv) An apparent-depth map is obtained by subtracting uncorrected DEM estimates from the water surface elevation estimates. (v) Equation (1) is used to generate real-depth estimates which are then combined with the water elevation estimates to produce corrected bed elevation estimates for wet points. (vi) The corrected water-surface elevation estimates are merged with the dry-bed DEM, provided it is clear that after the correction, the bed has indeed been seen. Finally, (vii), interpolation from the corrected bed elevations, based upon Delaunay triangulation, is used for locations where the analysis suggests that the bed has not been seen.

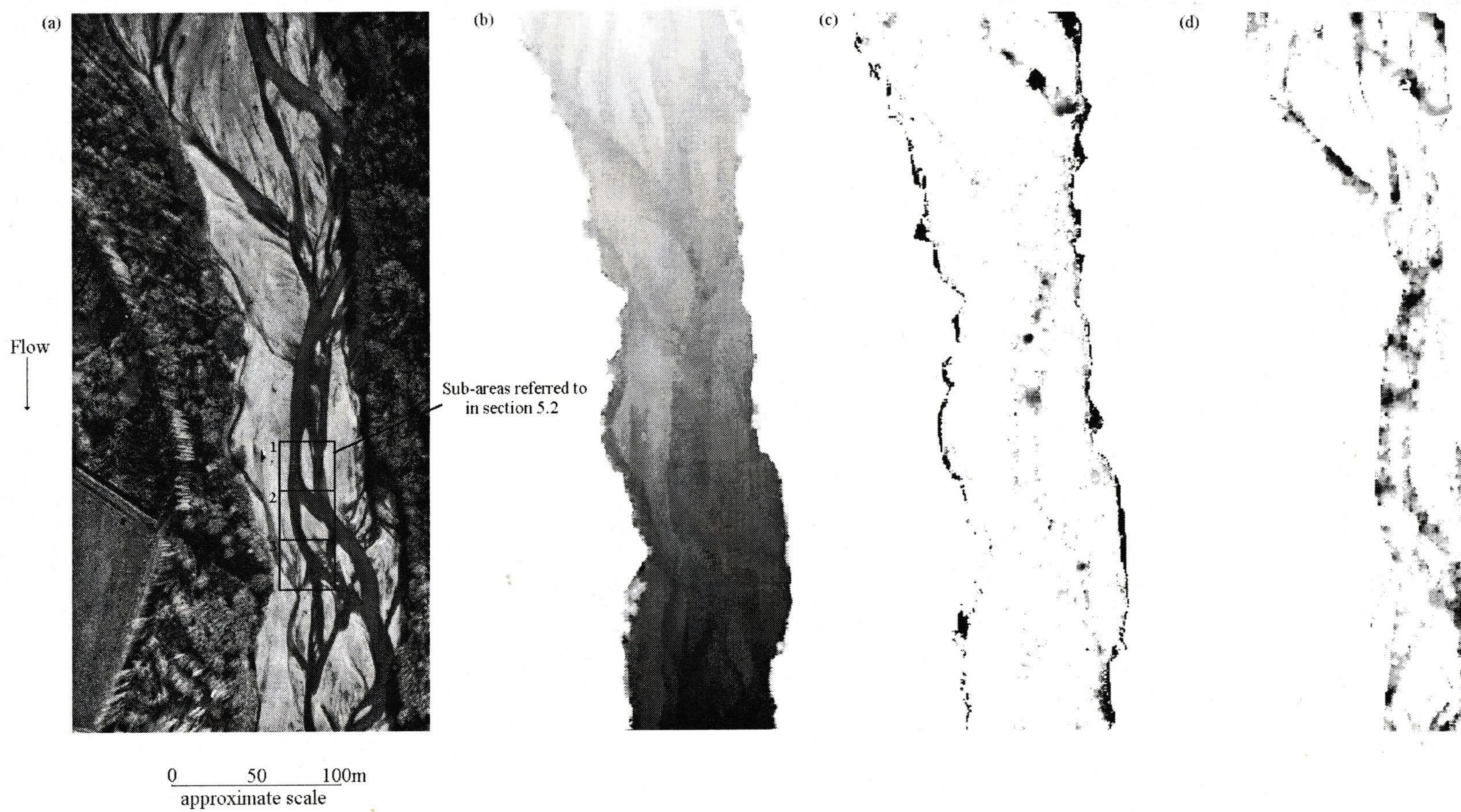


Figure 1: Figure 1a shows the North Ashburton River study area. Figure 1b shows an uncorrected DEM of this area, scaled from elevations of 48m (black) to 55m (white). Figure 1c shows the changes in elevation due to the correction procedure, scaled from 0m (white) to -0.5m (black). Figure 1d shows the water depths derived during the correction procedure, following correction, scaled from 0.0m (white) to 0.8m (black).

Another issue emerged during development of this algorithm. One of the effects of refraction is to reduce the extent to which the perspective projection holds. Our correction procedure does not deal with this explicitly through the collinearity equations but *post hoc*, after initial bed elevations have been derived. However, the stereo-matching process associated with digital photogrammetry requires that some consideration is given to this. The effect of refraction will be lateral shifts in image position, such that it will be necessary for the stereo-matching algorithm to search more widely for matching pixels. Thus, after some testing of the algorithm, we have established that the maximum parallax parameter should be increased. This is important as it means that the stereo-matching process searches a greater z-elevation range, which is necessary given the effects of refraction upon the apparent depth of points.

4 Field data

The test field-site was a 430-m long reach of the North Branch of the Ashburton River, South Island, New Zealand (Figure 1a). The active braidplain is approximately 100 m wide and is characterised by low vertical relief (1–2 m). Aerial photography and concurrent ground survey were undertaken in May 1995, during a period of low river flow. A pair of stereo photographs at 1:3000 scale were taken with a calibrated Zeiss LMK15 camera. A logging Total Station instrument was used to survey six photo-control targets and 3500 check points, 54% of them under water. The stereo-pair was scanned at 12.5 microns into 256 shade grey-scale using a photogrammetric scanner, to give object space pixel dimensions of 0.038 m. DEM generation using digital photogrammetry was performed using the OrthoMAX professional module of ERDAS Imagine software installed on a SUN workstation.

5 Results

5.1 Photogrammetric DEM

Figure 1b shows the uncorrected DEM, collected with grid-spacing of 1 m, for the study reach. This shows that the method generates an excellent basic topographic representation even without any through-water correction, with clear identification of the braidplain morphology. Figure 1c shows the elevation changes due to the correction procedure. The magnitude of these varies spatially. The maximum change is about 0.5m and occurs where the water is deep and the photogrammetry sees the water surface; these points are removed by the correction algorithm. This type of correction is likely to result in an important basic improvement in topographic representation. The smaller changes are where the refraction component of the correction is important. Figure 1d shows water depths derived during the correction process, following refraction correction and removal of points where it was felt that the water surface (not the riverbed) was detected.

5.2 Accuracy

The accuracy of the photogrammetry-generated DEM was assessed over three sub-areas by comparison with the independently-acquired ground measurements (Table 1). The mean error (ME) shows only small, cm-scale, bias in the mean bed level. The standard deviation of error (SDE) can be compared with a best-expected theoretical precision for individual points of 0.04 m. Thus the photogrammetric results are downgraded from what would be expected. This arises both from the triangulation stage of the analysis and, more importantly in this case, from the difficulty of sampling complex gravel surfaces. This is a sampling problem where at the scale of the DEM resolution (0.37 m), there will be surface variation due to individual clasts which, given the point sampling by survey pole during the ground survey, will produce an elevation range that is greater that the optimal precision of the survey.

The values of ME and SDE for the uncorrected wet bed points are greater (p less than 0.05). Evidence from the three study areas suggests that this is water depth dependent (Figure 2a). This reflects two processes: (i) as water depth increases, errors due to refraction increase (both the real *versus* apparent depth effect and the stereo-matching effect); and (ii) in very deep reaches, the photography will see the surface rather than the bed. Introduction of the correction procedure results in a reduction in mean error in all three sub-areas. The explained variance (R^2) increases in sub-area 1, but falls in sub-areas 2 and 3. This is as expected: the correction procedure cannot improve the level of correspondence, but it can improve the bias in the correspondence. Thus, the correction removes the systematic error that arises from the combined effects of refraction and deep water.

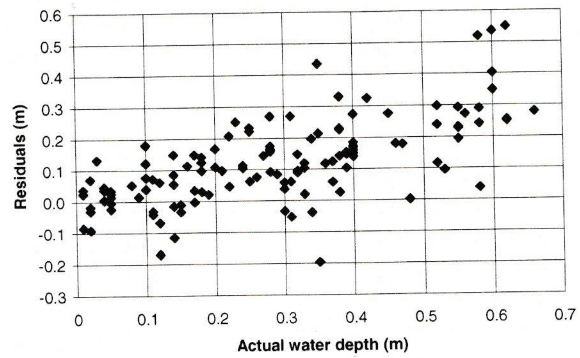
Table 1: Accuracy assessment for three sub-areas for exposed areas (1a), uncorrected submerged areas (1b), and corrected submerged areas (1c).

1a: Exposed areas	R^2	*ME (m)*	*SDE (m)*
Sub-area 1	84.7%	0.008	0.083
Sub-area 2	89.7%	0.012	0.071
Sub-area 3	90.8%	-0.052	0.055

1b: Submerged areas (uncorrected)	R^2	*ME (m)*	*SDE (m)*
Sub-area 1	37.9%	0.192	0.144
Sub-area 2	63.3%	0.076	0.090
Sub-area 3	71.3%	0.056	0.072

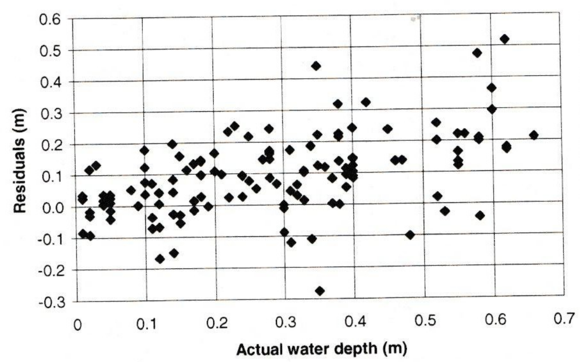
1c: Submerged areas (corrected)	R^2	*ME (m)*	*SDE (m)*
Sub-area 1	46.1%	0.143	0.136
Sub-area 2	62.5%	0.034	0.100
Sub-area 3	62.0%	0.055	0.086

a



	Zone 1 (<0.2m)	Zone 2 (0.2-0.5m)	Zone 3 (>0.5m)
ME (m)	0.029	0.139	0.284
R^2	0.056	0.017	0.186
Slope	0.306	0.192	1.501

b



	Zone 1 (<0.2m)	Zone 2 (0.2-0.5m)	Zone 3 (>0.5m)
ME (m)	0.028	0.110	0.205
R^2	0.040	0.001	0.154
Slope	0.288	0.055	1.422

Figure 2: The overall relationship between water depth and error between photogrammetrically-derived and surveyed elevations for (a) uncorrected and (b) corrected DEMs of the three sub-areas.

The success of the correction procedure would also appear to be water depth dependent (Figure 2b). Between about 0.0 m and 0.2 m water depth, the ME is low without correction, and after correction it is reduced by only 0.001 m to 0.028 m. Scatter remains high, reflecting the similar limits to any agreement between survey points and photogrammetric points identified for exposed areas. Between about 0.2 m and 0.5 m, there is a stronger sensitivity to water depth prior to correction (Figure 2a, slope of 0.192), and correction reduces this sensitivity (Figure 2b, slope of 0.055), with a corresponding decrease in ME of 0.029 m. Thus, the association between water depth and error is eliminated through introduction of the correction (both slope and R^2 are reduced). There are very few points deeper than 0.5 m. The mean error of those points is reduced by the correction (from 0.284 m to 0.205 m) but there remains a strong association between water depth and point error, even after the correction, with both slope values and R^2 values after corrections remaining significant. What emerges from these results is that there is a depth zone where correction makes a major difference to the quality of results that are obtained. Beyond this zone, further increases in quality are possible, but limited by the fact that the photography 'sees' fewer points at greater depths.

Sediment storage in a river reach can be represented by the mean bed level (MBL) over the reach area. As shown from the test areas, the uncorrected and corrected photogrammetry approaches induced residual biases (i.e., ME) in the mean bed level over wetted areas that locally ranged up to 0.19 m. However, wetted channels covered only a small proportion of the North Ashburton braidplain, and for the whole study reach (wet and dry) the MBL obtained by the corrected photogrammetry procedure was within 2 mm of the ground-truth value obtained from the Total Station dataset. Cross-section surveys simulated from the Total Station dataset showed that sections would have to be spaced less than 45 m apart to match this accuracy of reach mean bed level determination.

6 Conclusions

This study demonstrates the utility of digital photogrammetry to surveying braided gravel riverbeds. Using 1:3000 scale imagery it is possible to get very small surface elevation errors (standard errors less than 8 cm) for exposed areas, comparable with the size of the riverbed gravel and therefore the sampling error of point measurements by ground-survey. Errors in submerged zones were greater, but introduction of a fully-automated correction procedure resulted in the removal of at least some of the systematic bias. The overall error in mean bed-level for the 430 m long reach of channel was 2 mm. Thus, this method has the potential to revolutionise monitoring of wide gravel-bed rivers, particularly those with clear-water, as the time required for field data collection is substantially reduced.

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