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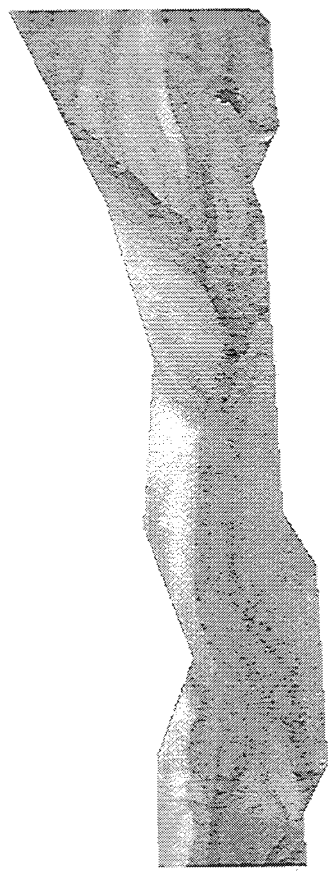

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Cover: Aerial photograph and digital elevation model of the study reach,
North Ashburton River at Thompson's Track Bridge.

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Contents

Abstract

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Surveys of riverbed and channel topography are key requirements for effective river channel management. Historically, rivers in New Zealand have been monitored by using a series of re-surveyed cross-sections. However, the spacing between successive cross-sections and the frequency of re-survey are often determined by practical issues rather than consideration of the nature of channel change or uncertainty in the results. Digital photogrammetry represents a technique that may provide a cheaper, more efficient, and more accurate method of monitoring riverbed morphology, detecting river channel change, and so improving river channel management. This report focuses on the use of digital photogrammetry to provide topographic information for wide gravel-bed rivers by considering its application to specially flown imagery of the North Ashburton River. First, some fundamentals of digital photogrammetry are introduced. Next, some practical issues concerned with planning a photogrammetric project are discussed, including a consideration of the quality of topographic data obtained. Finally, a procedure for dealing with areas where there is water is described and applied to a reach of the North Ashburton River. Results are assessed in terms of point accuracy and reliability (with respect to water depth distribution and sediment storage). Overall, the results are found to be very encouraging, producing mean elevation errors over dry parts of the riverbed that are smaller than the average grain size of the riverbed material. In submerged areas, a systematic bias is found, but this is substantially reduced after application of the correction procedure. The photogrammetric output is also found to be ideally suited to river management applications such as habitat assessment and mean bed level calculations.

Introduction

Surveys of riverbed and channel topography are key requirements for effective river channel 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 apportioning 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 conventional approach to monitoring New Zealand's riverbeds has been to establish a network of cross-sections which is 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. Indeed, cross-sections often tend to be sampled at a spatial and temporal frequency that is a function of the importance of the particular river reach to the engineer. An example is provided by the braided Waimakariri River, northwest of Christchurch. The spatial density of cross-sections is highest (200 m spacing) in the lower reaches, nearer the coast, where it is necessary to monitor aggradation and gravel extraction. This area is also of most immediate concern to the residents of Christchurch where a stop bank is located on the true right bank to prevent catastrophic flooding. Further upstream, the cross-section spacing increases to 800 m.

Are our cross-sections spaced closely enough, and are they surveyed frequently enough? Designing the appropriate section spacing is a tricky issue, particularly in braided rivers which are markedly complex in their topography and behaviour, and requires prior detailed knowledge of the riverbed topography. Lane *et al.* (1994) found that for a European proglacial braided river, cross-section spacing needed to be as small as 3 m if volumes of erosion and deposition were to be quantified with sufficient accuracy. Although this river was smaller than those of the Canterbury Plains, and one would intuitively expect the acceptable spacing to increase in proportion to channel width, there is currently little knowledge of just how close the spacings should be for a river such as the Waimakariri.

The time between surveys should reflect the issue of interest and is also related to the cross-section spacing. For monitoring long-term aggradation or degradation, the time interval should be sufficiently long that a signal emerges from the "noise" induced by sampling the river at a limited number of cross-sections. However, to monitor change due to floods (such as gravel movement or channel migration), surveys should be more frequent. With this, the cross-section spacing is constrained by the number of cross-sections that can be surveyed before the next flood occurs. As with the cross-section spacing problem, it is not known just how frequently it is necessary to survey a large river like the Waimakariri to detect sufficient morphological information to quantify river channel dynamics.

Even if the required density of cross-sections and frequency of re-surveys were known, there remains a critical logistical limitation on the cross-section approach, and it is rarely possible to capture a "snapshot" of the topography of a river reach. For example, it may take several years to complete a single survey of a cross-section network for a long reach of a large river.

With these issues in mind, this report is concerned with the development of digital photogrammetry, coupled to automated image analysis, as a technique that may provide a cheaper, more efficient, and more accurate method of monitoring riverbed morphology, detecting river channel change, and so improving river channel management. Our focus is on wide gravel-bed rivers, which appear to offer the best potential, and this report considers its application to specially flown imagery of the North Ashburton River. Many New Zealand riverbeds have been captured on numerous occasions by historical aerial photography, and the methods reported here could be repeated for reconstruction of channel change. The report details: (i) the basic principles of photogrammetry; (ii) issues surrounding the application of automated digital photogrammetry to gravel-bed rivers; (iii) a consideration of controls on photogrammetric data quality; (iv) the development of a special method for dealing with locations where there is water; and (v) application to the North Ashburton River. The last section includes a comparative evaluation of the merits of a photogrammetric approach over and above an approach based on cross-section monitoring.

Digital photogrammetry

Basic principles

Digital photogrammetry is a technique that allows automated extraction of topographic data from overlapping digital imagery (e.g., aerial photographs scanned into a digital format). It has its origins in conventional 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 (Figure 1). 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 ground coordinates of that point.

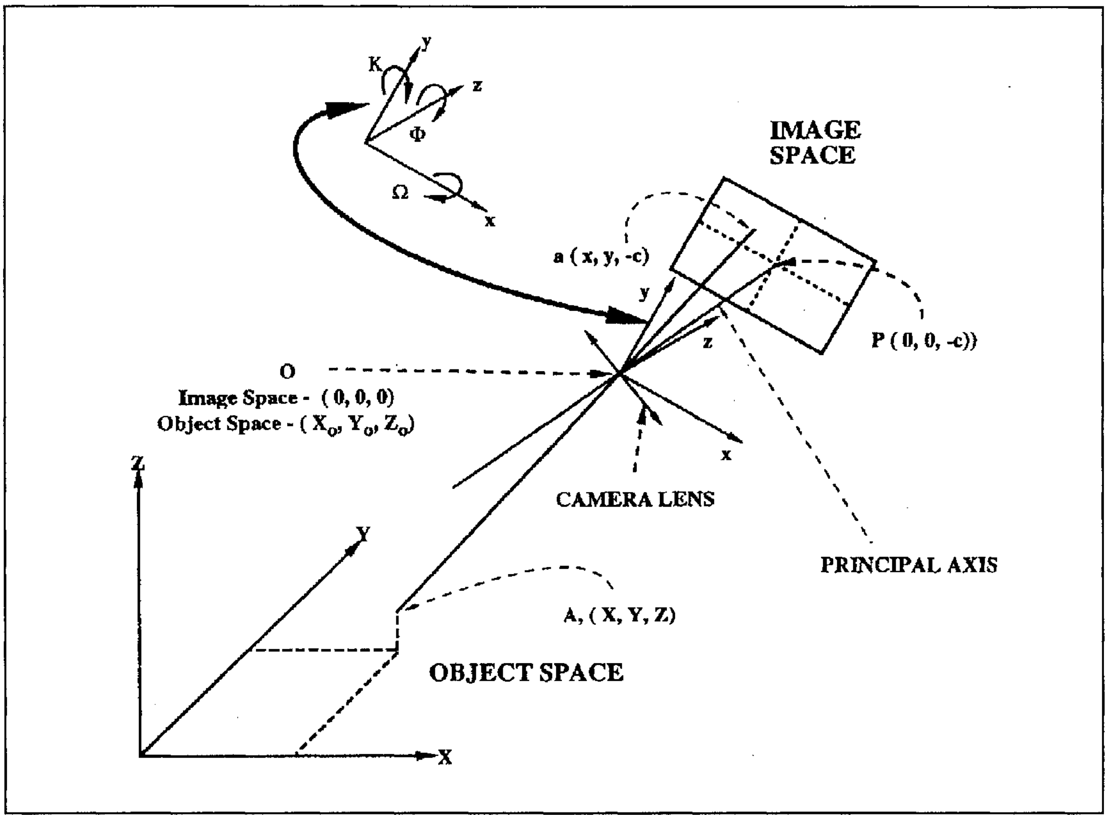


Figure 1: **The relationship between points in the object space and image space for an ideal photograph.**

Until the early 1970s, photogrammetry was fully manual, requiring vertical aerial photographs which were mounted in a stereo-comparator, and scaling factors were used to reconstruct mechanically the relationship between object space and image space. In the 1970s and 1980s, there was a gradual shift towards an analytical approach. This involves treating the relationships mathematically rather than mechanically. This was done by an expensive piece of hardware called an analytical plotter. The main advantage of this approach was two-fold. First, although manual digitisation of the stereo-pair was still required, the mathematical approach produced data in digital form, so allowing data manipulation using terrain modelling software. Second, the approach allowed the analysis of oblique imagery. However, these advantages aside, two major problems remained. First, the required hardware was (and still is) expensive, restricting photogrammetric applications to a few commercial companies and institutions able to afford the associated investment. Second, analytical photogrammetry still requires manual digitisation. A trained operator can collect up to 500 points per hour, but this collection rate is difficult to sustain for long periods of time.

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. This has two advantages. First, it can reduce significantly the time required to collect data (200 points per second is a typical data collection rate), so making the technique significantly less expensive. Second, the approach is much less dependent upon expensive hardware. The necessary software can be mounted on work-stations and even high-specification personal computers. 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 photogrammetry to be used much more widely for morphological monitoring.

Application to wide gravel-bed rivers

In theory, wide gravel-bed rivers, such as occur on the Canterbury Plains, should offer the best potential for photogrammetric analysis because for much of the time only small proportions of their beds are wetted. However, there remain three key issues to address, all of which currently require further research to allow the technique to be of greater practical use.

First, wide gravel-bed rivers have low relief as compared with the landforms normally studied using photogrammetry (e.g., coastal cliff erosion). This means that the technique must provide information on small height changes obtained from over a large surface area. This will limit the information that can be acquired from archival imagery and means that careful attention must be given to the design of specially flown imagery (see below).

Second, there are the inundated areas, however small a proportion they may be of the total riverbed area. If the water is clear, photogrammetry may still be used, and a basic correction for the real versus apparent depth included by appropriate refraction modelling. This is developed in this report. If the water has some turbidity (but not too much), the bathymetric information may be acquired by digital image processing. For instance, different water depths may have different image signals, which can be classified to depth bands by empirical calibration with data obtained by ground survey. If the water is very turbid, and the bottom is not visible at all, underwater bathymetric information must be measured independently by field survey. Thus, this method has considerable potential, with some development, for monitoring gravel-bed rivers at low flows between floods, but is unlikely to be able to provide significant amounts of information during floods.

Third, there may be areas of the river that are vegetated, particularly those that are relatively stable. Whilst detection of the longevity and spatial extent of these areas over long time-periods is useful, and may be possible using digital image processing, detection of surface morphology will need some form of vegetation correction. This report presents preliminary progress with these issues from studies on a braided river (the North Ashburton) with clear water at the time of photography and with negligible vegetation cover on the braidplain.

Controls on photogrammetric data quality

Important controls on the quality of photogrammetric data include: (i) image resolution and quality; (ii) ground control; (iii) stereo-matching operation; and (iv) data density and distribution. Whilst each of these is critical, the main starting point is image resolution. Research has shown (e.g., Lane *et al.* in press) that provided the imagery is scanned using a photogrammetric scanner, critical camera properties are known (the camera is calibrated), and ground control of an appropriate quality is available, then the quality of the morphological information acquired can be predicted from the resolution of the imagery.

Image resolution and quality

The scale of the imagery, normally expressed as 1: *x*, is defined by the ratio of a camera's focal length to its flying height. The most straightforward source of imagery is a calibrated, large format, aerial survey camera. The film-based imagery that this supplies will need to be scanned directly from either negatives or diapositives (not prints) to a given resolution (*r* in microns) in the image space. The size of a pixel in the corresponding object space (*p* in metres) is defined by the scale of the imagery and the scanning resolution:

$$p = 10^{-6} xr \qquad [1]$$

This defines the theoretical best possible precision of elevation estimates from this imagery as *p*. In practice, this will be downgraded due to uncertainties introduced by ground control and camera calibration. As the stereo-matching process involves some form of areal correlation, the best possible planform resolution that can be obtained is about 5*p*. Thus, with imagery of scale 1:27 000, scanned at 12.5 microns, the best possible vertical resolution would be about 0.34 m and data could be collected at a 1.7 m spacing. With the analysis of archival imagery, the only means of improving these resolutions is by scanning at a higher resolution (r'). In theory, it is possible to scan at higher resolutions, but this will require an increase in image storage space of $(r/r')^2$. Thus, a 12.5 micron resolution large-format image scanned as grey-scale will require about 300 Mb of storage space.

With specially flown imagery, it is possible to vary *x* to improve vertical and planform resolution. For instance, 1:6000 imagery with the above scanning characteristics will improve vertical resolution to about 0.08 m and spatial resolution to 0.40 m. However, reducing *x* will reduce the coverage. Coverage is a function of the format (*T* in metres) of the imagery. The length of coverage on the ground (*l* in metres) of one image is given by:

$$l = xT \qquad [2]$$

Thus, with 1:27 000 imagery flown by a camera such as an RC8 with a square format, the length of coverage will be equal to the width of coverage and will be about 6.3 km. For photogrammetric analysis, a 60% overlap between consecutive images is normally required, producing a maximum length of 3.8 km along the flight path for any image pair from which photogrammetric data may be acquired. With 1:6000 imagery the photogrammetric coverage length would be about 800 m and coverage width would be 1400 m.

Ground control

The above calculations show that by reducing the scale of the imagery, the number of images required to produce a particular coverage can increase significantly. This not only increases the costs of additional analysis and data storage, but also the amount of ground control that is required. At least five ground control points must be common to both images in a stereo-pair. Ground control-points (GCPs) should be distributed across the full area of stereo-coverage for any image pair, and should be surveyed to a precision that is at least as good as the object space pixel size defined in Equation 1. They should also have minimum dimensions of 6x6 object space pixels, so that they are readily identifiable on the imagery. As more stereo-pairs are required, so more ground control is required. If consecutive images are going to be compared, then it is not necessary to assume that these GCPs are fixed through time *provided* that they are located within a fixed datum *and* they are surveyed at the same time as each photogrammetric sortie. In summary, it is important that any design of specially flown photography gives careful attention to both the advantages and disadvantages of reducing image scale.

The GCPs are used in a process called triangulation (or a 'bundle adjustment' in photogrammetric terms) to estimate the relationship between the image space and the object space at the time when the imagery was acquired. It is a critical phase of the analysis, and is the stage at which it is possible to confirm the quality of the data that will be acquired. The process, based upon least-squares estimation, recognises the knowns (GCP positions, image coordinates for each GCP on each image, camera calibration, assuming a properly calibrated camera) and the unknowns (camera position and orientation). The knowns are assumed to have been measured with error and the unknowns will be estimated with error. Most triangulations will require an estimate of the error associated with each known, which will determine the extent to which they can adjust during the least-squares adjustment. It is critical that these estimates are sensibly specified: often, field survey will produce a much better precision than that defined by the scale of the imagery. Use of the field survey precision will over-constrain the adjustment, producing poor triangulation results. The triangulation will also provide an indication of the error associated with each unknown, which determines the quality of the data that the photogrammetry will provide.

Stereo-matching and data collection

Once an acceptable triangulation has been obtained, it is necessary to consider the parameters that control the performance of the stereo-matching algorithm and the density of data that will be collected. Research has shown that provided the triangulation is good, and the imagery is of an appropriate scale and contains sufficient texture, stereo-matching parameters have little effect upon photogrammetric data quality, except in areas of exceptionally complicated topography where there is a high density of breaks of slope (Lane *et al.* 1999). It is expected that this is also true for exposed areas of the braidplain. However, the extent to which it is also true for inundated areas needs evaluation. The stereo-matching software will normally provide an indication of the confidence that can be placed in a particular match being successful, and this is a useful indication of how effective the matching has been. The maximum density of data collection is defined by the spatial resolution estimated from Equation 1, but is sometimes downgraded by the triangulation results if this was not particularly successful. Notwithstanding this, the default or recommended density may be excessive, resulting in increased data collection and storage times. The optimal data collection density will be defined by spatial variation in surface topography, or surface roughness: with more complicated surface topographies, higher densities will be necessary, and this needs to be evaluated with respect to the properties of the surface under consideration. One alternative to this is feature-based stereo-matching, which seeks to include surface characteristics such as breaks of slope in the surface. This requires a more complicated data structure in storage, but can significantly improve surface representation.

Locations where there is water

The application of digital photogrammetry to rivers requires a special treatment in zones where there is water. This is a well-established weakness of the use of photogrammetry for monitoring river channels (Lane *et al.* 1994). Field surveying of rivers at low discharge is the most expensive solution to this problem, but the question remains as to whether or not photogrammetry can itself be developed to address this problem, so reducing the dependence upon field survey and allowing the potential for analysis of archival imagery where no field survey exists.

Correction for clear-water rivers

If the water is clear and not too deep (the latter being common 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 of refraction:

$$n = \frac{\sin i}{\sin r} = \frac{R}{D} \qquad [3]$$

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 (1.340 ± 0.007) for temperatures between 0 and 30 °C (Jerlov 1976). The approach developed in this paper is similar to that used by Fryer (1983), and is based upon assuming that, given estimates of D derived from combining digital photogrammetric output, it is possible to derive estimates of R and hence correct the original photogrammetric estimates of bed elevation.

The correction procedure is illustrated in Figure 2 and has been derived after a series of tests of each stage of the process. It proceeds as follows:

(i) the uncorrected 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 water's edge map using kriging;
(iv) an apparent depth map is obtained by subtracting uncorrected DEM estimates from the water surface elevation estimates;
(v) Equation 3 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 elevation estimates are merged with the dry-bed DEM, provided it is clear that, after the correction, the bed has indeed been seen; and
(vii) interpolation from corrected bed elevations, based upon Delaunay triangulation, is then used for locations where the analysis suggests that the bed has not been seen.

Interaction with stereo-matching parameters

One additional issue emerged during development of this algorithm. One of the effects of refraction is to reduce the extent to which the perspective projection holds (Figure 1). The correction procedure does not deal with this problem 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 slightly 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.

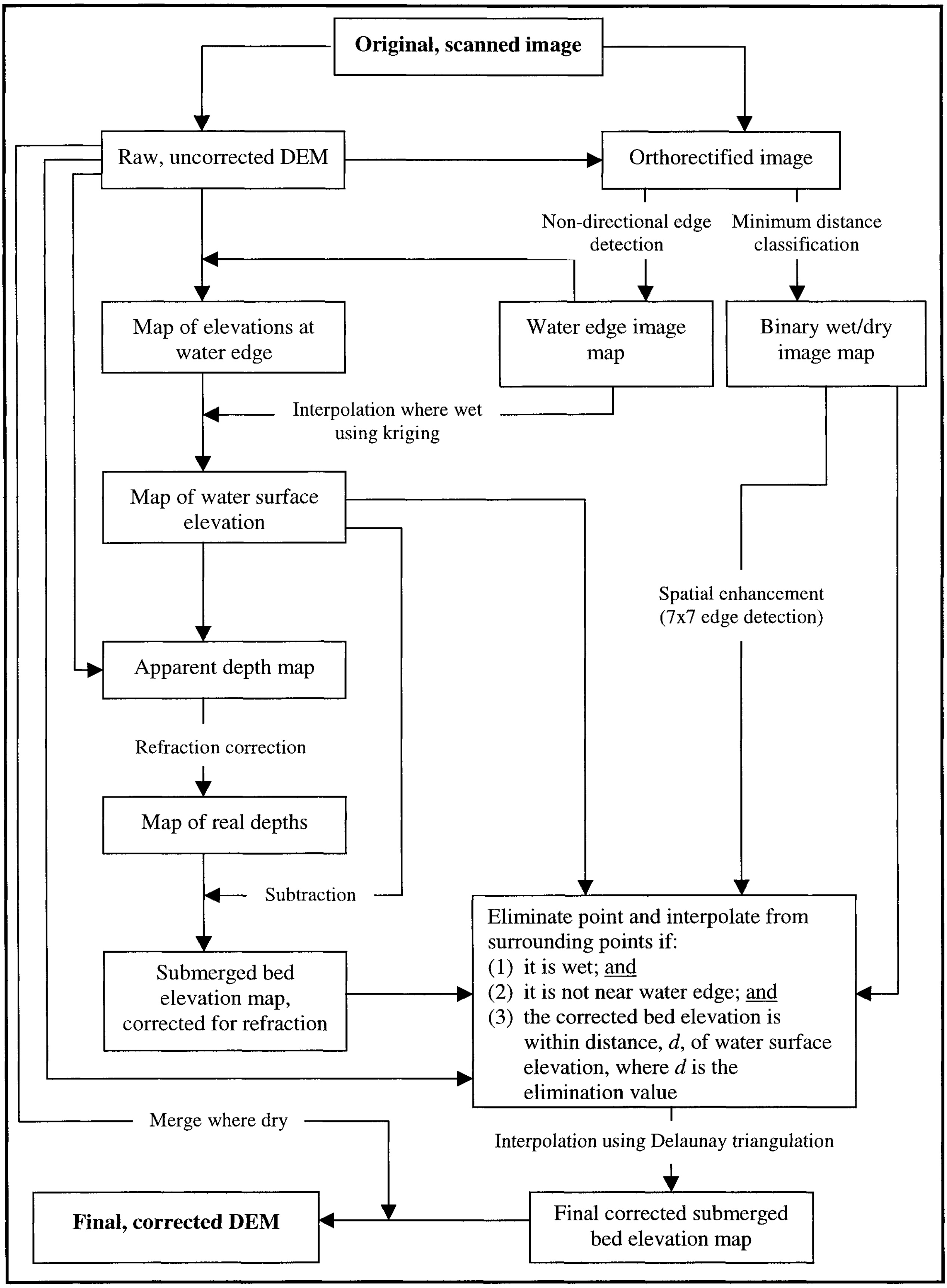


Figure 2: **The fully-automated digital elevation model correction procedure.**

Application to the North Ashburton River

The field site chosen for this application is a small reach of the North Branch of the Ashburton River, South Island, New Zealand, just upstream of Thompsons Track Bridge (Figure 3a). The active braidplain is about 100 m wide and is characterised by low vertical relief (1–2 m) as compared with the spatial scale. Aggradation has been measured in the reach since 1937, with a wedge of bed material accumulating at an average rate of 5.8 cm per year (Laronne & Duncan 1992). The reach was surveyed in May 1995 by NIWA using a Total Station and automatic data logger. Over a two week period, 3500 points were surveyed, of which 54% were under water. The sampling density was 7 m for exposed areas and 2 m in the wetted channels. DEM generation using digital photogrammetry was undertaken using a pair of 1:3000 scale photographs taken by Air Logistics (NZ) Ltd. using a calibrated Zeiss LMK15 camera at the same time as the ground survey. 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.

A permanent datum was defined using Thompsons Track Bridge. Photo-control was surveyed into this network using six control targets that were laid out before photography. The position of the targets was measured by Total Station. For accuracy assessment, a high density sample of points was obtained from within the reach, also using Total Station survey. Laboratory analysis used the OrthoMAX professional module of ERDAS Imagine software installed on a SUN workstation.

Results

Figure 3b shows the uncorrected DEM, collected with a grid-spacing of 1 m, for the whole North Ashburton study reach. This shows that the method generates an excellent basic topographic representation even without correction, with clear identification of the braidplain morphology. The magnitude of the elevation changes due to the correction procedure varies spatially (Figure 3c). The maximum change is about 0.5 m, which is associated with locations where the water is deep and the photogrammetry sees the water surface, and 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. There are locations where no large correction is required, and this reflects areas where the water depth is particularly shallow. These issues are explored quantitatively below. Figure 3d shows water depths derived during the correction process, following refraction correction and removal of points where it was felt that the water surface had been detected.

Accuracy assessment

The only truly independent means of assessing the accuracy of the DEM generation process is to compare extracted elevations with some independently acquired ground measurements (Torlegård *et al.* 1986). In this study, the ground survey was used for this purpose, and DEM accuracy was assessed in terms of explained variance (R^2), mean error (*ME*), and standard deviation of error (*SDE*). The last two are important, as they have been found to be more sensitive determinants of DEM quality (Li 1992). Accuracy assessment was undertaken for three sub-areas (Figure 3a), for which DEMs were collected with a smaller grid size of 0.37 m. The results are shown in Table 1.

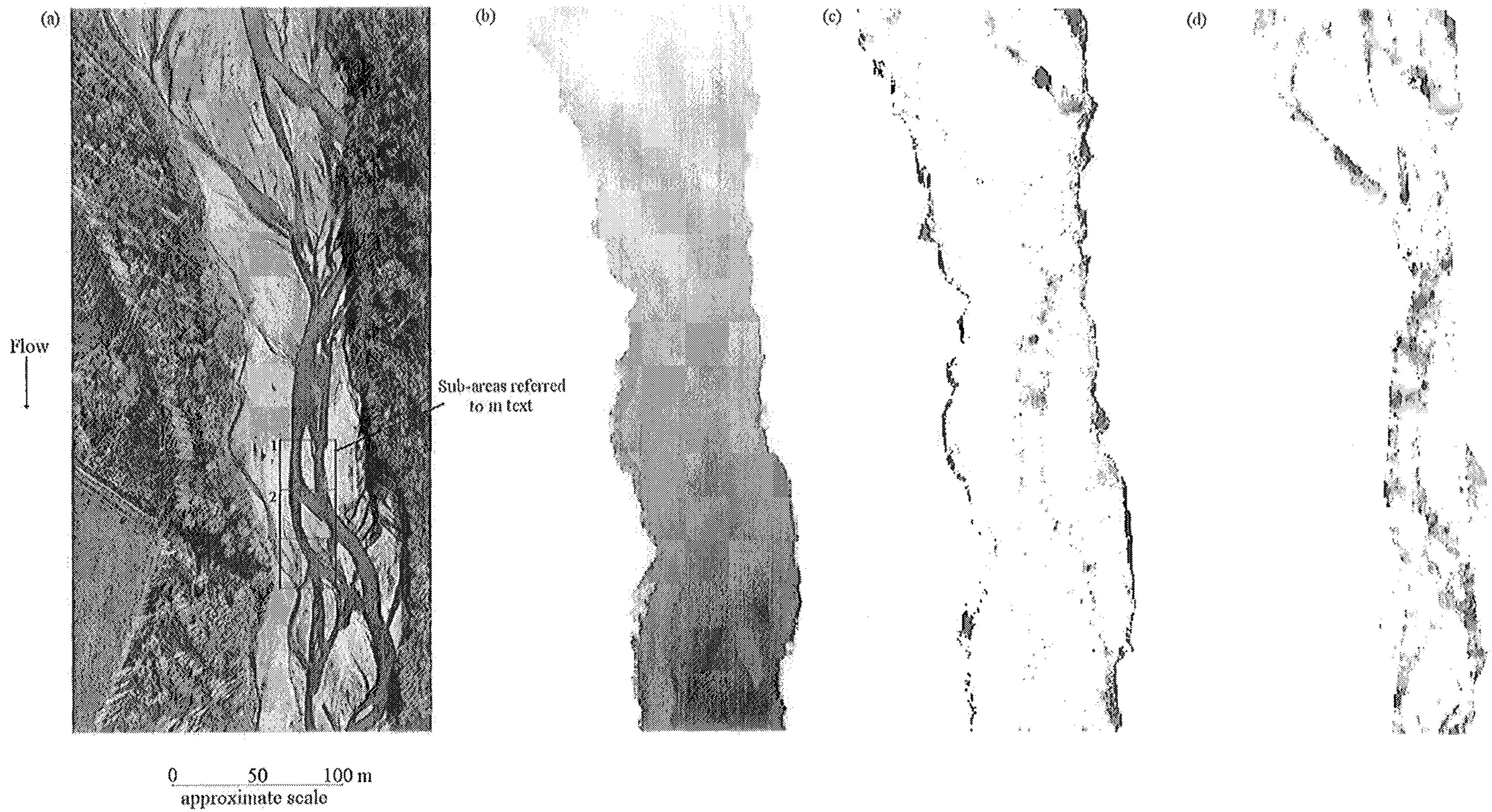


Figure 3: **(a) the North Ashburton River study area; (b) an uncorrected digital elevation model of this area, scaled from elevations of 55 m (white) to 48 m (black); (c) the changes in elevation due to the correction procedure, scaled from 0 m (white) to -0.5 m (black); (d) the water depths derived during the correction process, scaled from 0.0 m (white) to 0.8 m (black).**

Table 1: **Results from basic accuracy assessment for the three sub-areas for exposed areas, uncorrected submerged areas, and corrected submerged areas.**

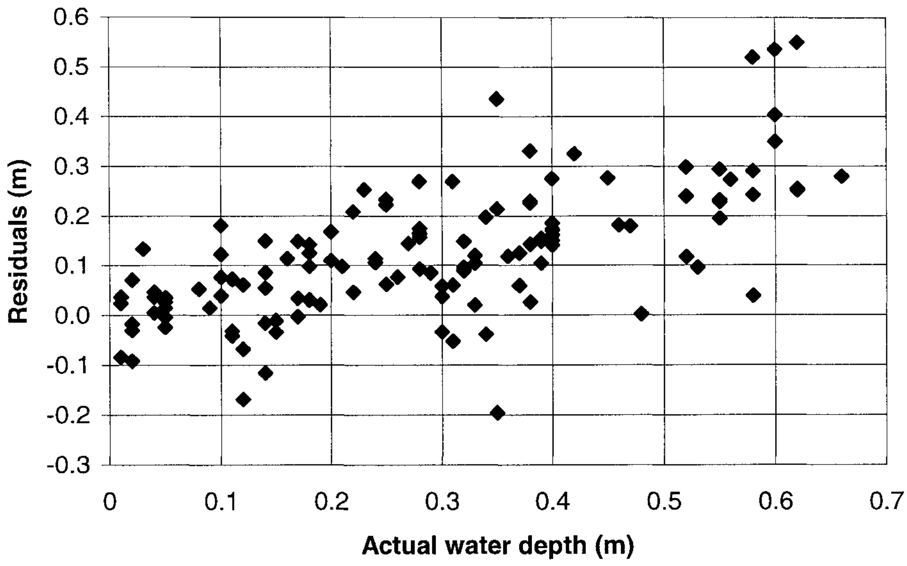
	R^2 (%)	*ME (m)*	*SDE (m)*
Exposed areas			
Sub-area 1	84.7	0.008	0.083
Sub-area 2	89.7	0.012	0.071
Sub-area 3	90.8	-0.052	0.055
Submerged areas (uncorrected)			
Sub-area 1	37.9	0.192	0.144
Sub-area 2	63.3	0.076	0.090
Sub-area 3	71.3	0.056	0.072
Submerged areas (corrected)			
Sub-area 1	46.1	0.143	0.136
Sub-area 2	62.5	0.034	0.100
Sub-area 3	62.0	0.055	0.086

Results for the exposed areas are particularly encouraging. The *ME* shows only small, centimetre-scale bias in the mean bed level. The *SDE* can be compared with a best expected precision (from Equation 1) 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 but, and more importantly here, 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 bad points are significantly greater (p less than 0.05). Evidence from the three study areas suggests that this is water depth dependent (Figure 4a). 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 be seeing the surface rather than the bed. Introduction of the correction procedure reduces 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.

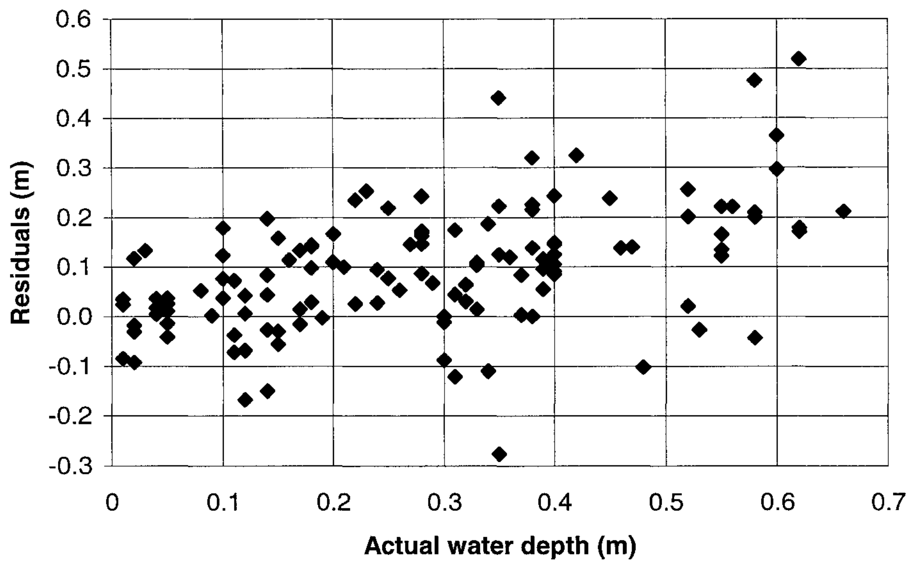
The success of the correction procedure would also appear to be water depth dependent (Figure 4b). Between about 0.0 and 0.2 m water depth, the mean error is low without correction, and after correction it is reduced by only 0.001 to 0.028 m. Scatter remains high, reflecting the similar limits to any agreement between survey points and photogrammetric points identified for exposed areas. Between about 0.2 and 0.5 m, there is a stronger sensitivity to water depth before correction (Figure 4a, slope of 0.192), and correction reduces this sensitivity (Figure 4b, slope of 0.055), with a corresponding decrease in mean error 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 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 correction 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 because the photography 'sees' fewer points at greater depths.

(a)



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

***Figure 4*: The overall relationship between water depth and error between photogrammetrically derived and surveyed elevations for (a) uncorrected and (b) corrected digital elevation models of the three sub-areas.**

DEM reliability assessment

Accuracy assessments can only go so far in helping the river manager to decide whether or not a photogrammetric approach is the right one to adopt. It is important to assess the implications of a photogrammetric approach vis-à-vis existing approaches in terms of the parameters that the manager might be interested in. These may be divided into information on (i) the distribution of parameters such as water depth that influence a river's ecological and recreational value, particularly at low flows, and (ii) changes in sediment storage.

Analysis of the sensitivity of water depth distributions to adoption of a photogrammetric approach as opposed to field survey is shown for the three sub-areas in Figure 5. It is clear that the distribution of water depths calculated from the uncorrected DEMs is heavily skewed towards shallower water than the actual water depths measurements. Correction has the effect of reducing the proportion of very shallow depths (less than 0.12 m) while increasing the number of points with intermediate depths (0.12 m to 0.36 m). As a result, the final water depth distributions are far more similar in shape to the actual distribution of water depths. This is particularly important for applications where water depth classification is used, such as models of the spatial distribution of riverine habitats, and shows the potential of digital photogrammetry.

Sediment storage in a reach can be represented by the mean bed level (MBL) over the reach area. As we have 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 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 *ME* obtained by photogrammetry would be expected to be considerably less than this. An estimation of MBL error can be obtained by extracting cross-sections at a variety of spacings, computing mean bed levels by the end-area method, and comparing them against the "ground truth" MBL obtained from the entire ground survey dataset (51.404 m). Figure 6a shows this analysis performed for the uncorrected and corrected DEMs: the correction procedure reduces the whole-reach MBL error from about 23 mm to about 2 mm. To put these figures into context, an MBL error of 1 mm corresponds to a volumetric error of about 35 m^3 over the whole 430 m long study reach.

It is now instructive to compare this level of bias against the sampling error in the reach MBL when the reach is represented by only a small number of cross-sections, as with a conventional monitoring programme. Figure 6b shows, as expected, that the estimate of reach MBL converges on the true value as the number of cross-sections is increased, but the error becomes less than the 2 mm bias in the MBL associated with the corrected photogrammetry only when the number of sections is greater than about 10. Thus to match the accuracy of the photogrammetry at defining MBL (and sediment storage volume) over the North Ashburton study reach, a ground survey would need to have sections spaced no further apart than about 45 m.

Conclusions

This report presents progress in the application of digital photogrammetry to the study of gravel-bed braided rivers. The results are particularly encouraging as compared with field survey, and using 1:3000 scale imagery, it is possible to get very small surface elevation errors (standard deviations of error less than 8 cm) for exposed areas. These are comparable with the D_{95} grain-size (6.4 cm) of the study reach and therefore the sampling error associated with point measurement. Errors in submerged zones were greater, but introduction of a fully-

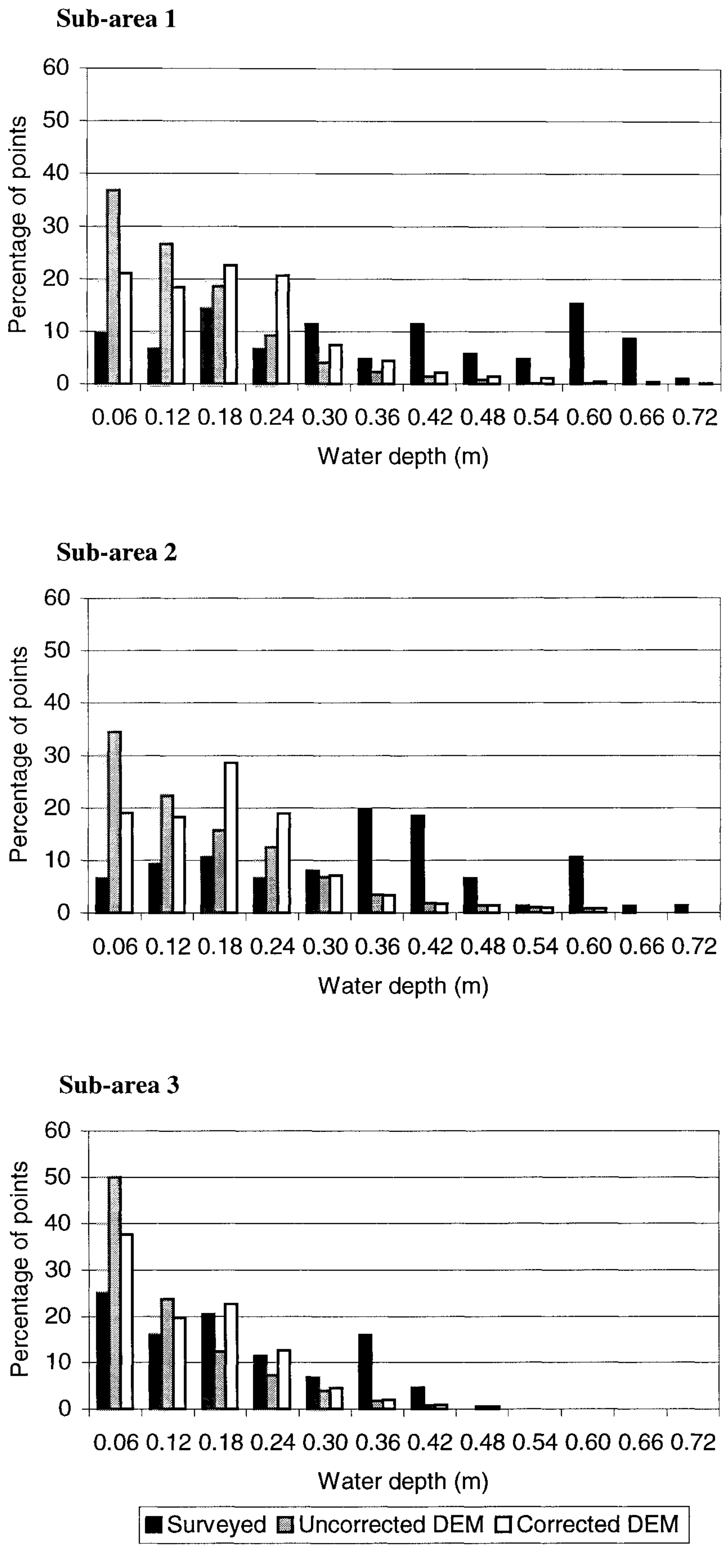


***Figure 5*: Comparison of the surveyed water depth distributions with those obtained from uncorrected and corrected digital elevation models for each sub-area.**

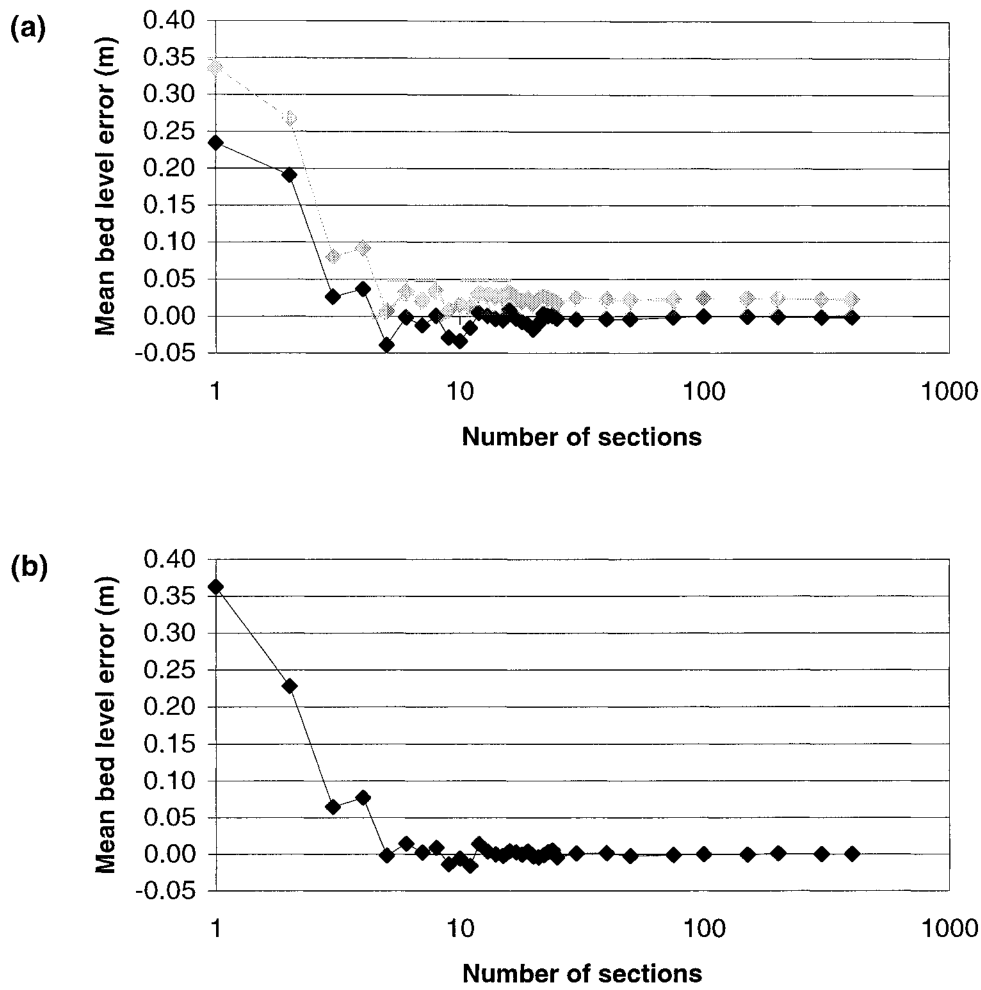


***Figure 6*: (a) a comparison of mean bed level error calculated from photogrammetrically derived digital elevation models before (grey) and after (black) correction; (b) the same analysis performed for field survey measurements.**

automated correction procedure resulted in the removal of at least some of the systematic bias. The overall error in mean bed-level for a 430 m long reach of channel was 2 mm. Thus, this method has the potential to revolutionise the monitoring of wide gravel-bed rivers, particularly those with clear water, as the time required for field data collection is limited to ground truthing and is therefore significantly reduced.

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References

Fryer, J.G. 1983: A simple system for photogrammetric mapping in shallow water. *Photogrammetric Record 11 (62)*: 203–208.

Jerlov, N.G. 1976: Marine optics. Elsevier Publishing Company, Amsterdam. 231 p.

Lane, S.N., James, T.D., & Crowell, M.D. in press: The application of digital photogrammetry to complex topography for geomorphological research. *Photogrammetric Record.*

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

Laronne, J.B. & Duncan, M.J. 1992: Bedload transport paths and gravel bar formation. *In* P. Billi, Hey R.D., Thorne C.R., & Tacconi P. (Eds.), Dynamics of gravel-bed rivers, pp. 177–202. Wiley, Chichester.

Li, Z. 1992: Variation of the accuracy of digital terrain models with sampling interval'. *Photogrammetric Record 14 (79)*: 113–128.

Torlegård, K., Östman, A., & Lindgren, R. 1986: A comparative test of photogrammetrically sampled digital elevation models. *Photogrammetria 41*: 1–16.