MEASURING RIVER-BED AND FLUME MORPHOLOGY AND PARAMETERISING BED ROUGHNESS WITH A KODAK DCS460 DIGITAL CAMERA

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ABSTRACT

Hydraulic engineers and fluvial geomorphologists need to understand how moving water flows over stream beds, and results in sediment transport. One critical aspect that is becoming increasingly important is gaining knowledge about the exact shape and morphology of water worked sediments. This paper demonstrates how automated terrain model extraction software combined with images acquired using a Kodak DCS460 digital camera have been effective in generating digital elevation models (DEMs) to represent such complex bed morphology and derive estimates of bed roughness.

The automated extraction of DEMs to represent sedimentary forms created in a flume requires careful photogrammetric design. In addition to the normal constraints imposed by scale and photo-configuration, the estimation and stability of camera inner orientation are critical. The approaches adopted and recommended are illustrated by recent research projects carried out on large flumes at Loughborough University and Hydraulics Research, Wallingford, both in the UK. The methodology has also been developed and applied to a real and large braided river channel system in the Canadian Rockies, using oblique imagery acquired with the DCS460. These three applications show the efficacy of the approach and demonstrate that morphological data has been collected at significantly higher spatial and temporal densities than is possible using other methods available.

Automated digital photogrammetry now provides hydraulic engineers and fluvial geomorphologists with an ability to measure at the bedform scale and partly at the grainscale. Manipulation of these base morphological descriptors and data derived from them, is becoming increasingly necessary for understanding fully, fluvial flow and sediment transport mechanisms.

1 INTRODUCTION

Riverbed morphology develops from the action of water flow and sediment movement, which are, in turn, influenced by the bed morphology. This link between bed form and hydraulics functions at a variety of scales, from individual grains, through to bedforms and to the stream channel itself. Clearly these scales are linked, with collections of particles creating the bedform and the spatial distribution of bedforms creating channel-scale topography. These different scales of bed topography influence fluvial processes in a variety of ways. For example, particle erosion and deposition depend upon grain size (Shields, 1936) and grain packing and bedform geometry (Kirchner *et al.*, 1990).

Despite the significance of riverbed topography at these different scales, measurement of other parameters such as flow velocity and turbulence has dominated fluvial research, whilst bed topography is often reduced to simple statistical or descriptive values. One of the main reasons for this emphasis has been the difficulty involved with measuring bed morphology, particularly over the range of spatial scales. In the few studies that have involved bedform measurement, the difficulties have forced researchers to measure profiles, typically across the river channel (e.g. Robert, 1998; Nikora *et al.*, 1998). Traditional measurement procedures (i.e. level and staff) result in slow rates of data acquisition, which can compromise studies in two mutually exclusive ways. Cross-sections may be spaced too widely, so that whilst change across the channel is monitored effectively, it is difficult to quantify downstream change. If however, an appropriate density of cross-sections is maintained, then frequency of survey is inevitably reduced such that data maybe sampled at a frequency that is lower than the time scale of change. If understanding is desired at the smaller grainscale, then these issues are compounded further because of the need for a far denser sampling strategy than conventional surveying methods can allow. Even if the study is transferred to the flume environment where many of the practical problems associated with carrying out fieldwork are eased, topography is traditionally measured using manual point gauges, which again leads to difficulties in achieving appropriate data densities.

Technological advances have enabled faster and hence higher resolution data acquisition methods to be used and developed. The recent computerization and automation of point gauges (Wallingford, 1999) has enabled individual cross sections to be measured more efficiently in a flume. The time required for each measurement point is still high and so measuring repeat parallel profiles to provide a digital elevation model (DEM) is an exceptionally slow process. Laser based instrumentation has offered potential for flume work also, with gantry mounted laser profilers being capable of deriving very dense DEMs. However, the time required for such measurement remains long also and problems of defining a stable reference plane suggest that this approach is only practicable within small areas (< $0.1m^2$). For natural field channels, developments in conventional surveying equipment are significant, particularly the motorized prism tracking Total Station. This technology has enabled the number of points that can be measured per day to be doubled (approximately 2-3000 points), and on secure sites provides a 50% reduction in personnel. The Total Station can certainly provide data at the channel scale and in all directions, but the density of points is only just able to provide information at the bed scale and is certainly incapable of providing anything at the more elusive grain scale.

2 A PHOTOGRAMMETRIC SOLUTION

A photogrammetric method of deriving appropriate data for fluvial research would appear to offer potential, and indeed photogrammetric methods have been used in earlier studies. Lo and Wong (1973) used 35mm cameras to examine the development of rills and gullies on a small section of weathered granite in Hong Kong. Collins and Moon (1979) measured stream bank erosion photogrammetrically and this was developed by Welch and Jordan (1983) where non-metric 35mm imagery was used to measure cross sectional profiles and 3D terrain models to represent change occurring in a dynamic meander bed. More recently, Lane *et al*. (1994) combined analytical photogrammetry with tacheometric methods to quantify change occurring in a rapidly evolving braided pro-glacial channel in the Alps. A Wild P32 camera was used to acquire highly-oblique terrestrial images and this study demonstrated just how improved topographic monitoring could assist fluvial research, (Lane *et al*., 1996).

These studies were dependent upon traditional photogrammetric methods, required access to expensive analogue/analytical plotters and relied upon manual measurement methods. Developments in digital photogrammetry have provided fresh impetus to the use of photogrammetry in fluvial research. There are many major advantages with a purely digital solution, particularly if a high-resolution digital camera is included. The equipment necessary for image measurement is becoming progressively less expensive, particularly with increasing use of PC platforms. The costs of high-resolution digital cameras remain high, but are decreasing (Ahmad and Chandler, 1999) and the spatial accuracy achievable is impressive, (Fraser, 1997; Shortis *et al*., 1998). Competition in the photogrammetric software market is intense also, with prices reducing and capabilities increasing. Of significance to fluvial researchers is the trend towards software which demystifies photogrammetry, encouraging non-photogrammetrists to apply the techniques, (Chandler, 1999). Most significantly, the software is capable of extracting very dense digital elevation models automatically and at very high rates. This means that DEMs can be derived at spatial and temporal frequencies that are far more appropriate to understanding the fluvial processes effecting change.

Water worked surfaces are ideal for automated photogrammetric measurement. The lack of vegetation and natural texture ensures that the surface measured coincides with the desired surface, unlike automatic terrain measurement for conventional urban mapping where vegetation and buildings create undesirable artifacts. The DEM acquisition procedure itself is also enhanced by obtaining imagery using a digital camera, which has a higher dynamic range and improved contrast when compared to an analogue image and scanning solution, (Graham, 1998). Image contrast is also maximized through the short camera to object distances used, which minimizes image degradation due to atmospheric haze Finally, the digital camera provides the obvious advantage of instant appraisal of exposures and of course removes the time consuming and expensive film processing and scanning phases.

These combined advantages, reinforced by work in related fields (e.g. Helming *et al*., 1992, Gruen, 1994; Brunsden and Chandler, 1996) convinced the authors that a stream bed measurement system based upon digital photogrammetry and a high-resolution digital camera was an appropriate technology to invest in and develop. Research grant funding enabled the purchase of a Kodak DCS460 and DCS420 and purchase and maintenance of the Erdas Imagine/OrthoMAX and OrthoBASE software packages. This combination has subsequently been used upon a diverse range of fluvial projects, both in terms of scale, location and desired outcomes.

3 CASE STUDIES

3.1 Tilting flume

The first project was carried out on the 1.2m wide "Tilting Flume" located at Hydraulics Research, Wallingford, an important center for fluvial research in the UK. The significance of the tilting flume project was the ability to directly compare DEMs generated by digital photogrammetry and an independent laser profiling system. A small area of the existing flume bed (0.25 x 0.25m) was being measured using a Keyence (LC2450) laser displacement sensor, mounted upon a horizontal motorized displacement frame, at a resolution of 0.5mm. Each experiment lasted for three weeks, with the bed surface measured at the end of each day, normally with a shallow depth of water (<0.10 m) and negligible flow rate. The disadvantage with the laser-based approach was the six hours required to measure the DEM combined with its limited spatial coverage. Digital imagery of the bed was captured using the DCS460, the DCS460 and DCS420 synchronized and a Hasselblad semi-metric camera, in order to assess the accuracy achievable using cameras of varying type and inner geometry. The cameras were mounted on a frame 1.9m above the flume bed and 10 conventional control points were placed on the flume edge and co-ordinated using theodolite intersection methods. The sensors were calibrated using both in-situ and test-field self-calibration methods, both methods being appropriate for establishing camera inner orientation, (Chandler *et al.*, in press). DEMs were generated automatically at a resolution of 3mm over an area of 1.1 x 0.8m using OrthoMAX. Point elevations within the 0.25 x 0.25m area measured by the laser profiler were then downgraded to a resolution of 3mm and these 6889 points were compared with the photogrammetric estimates to obtain the r.m.s.e. accuracy assessments presented in Table 1. The results show that there is little variation with sensor type, but that accuracies were not high when compared with the low camera/object distance of 1.9m. Detailed examination of the surfaces derived showed that the major discrepancies occurred between large particles in small regions of "dead ground" and so the size of the bed material in relation to the pixel scale is a dominant control (Section 4.0). However, the accuracy achieved is acceptable for fluvial research and of greater significance was the increased areal coverage (1.1 x 0.8m) and marked reduction in time required to obtain the imagery (only 10 minutes), which allows experimental work to continue.

Sensor type	r.m.s.e. (mm)
DCS460	±1.9mm
DCS460/DCS420	±2.0mm
Hasselblad	±2.0mm

Table 1. Accuracies of sensor type

Additional elements of research involved developing and assessing the potential of two-media photogrammetry and deriving estimates of bed roughness from the digital elevation models. The two-media photogrammetry has allowed imagery to be obtained through a shallow depth of water, without draining the flume and is reported upon more fully in Butler *et al.*, in press). Bed roughness has been quantified using a diverse range of methods, including texture extraction using the Hurst operator, Fast Fourier Transforms and generation of semi-variograms and semi-variance surfaces. Semi-variance surfaces have proved most valuable, because these have demonstrated that roughness can be parameterized at different scales and can therefore be used to define boundary conditions for numerical flow models (Butler *at al.,* 1998; Butler *et al,* in press).

3.2 The Flood Channel Facility

A second project carried out at Hydraulics Research Wallingford required generating DEMs of bed forms created in the Flood Channel Facility (FCF). This comprised a large meandering sinusoidal channel with a wavelength of 15m and channel width of 1.6m. The meandering pattern covered an area 15 x 8m making efficient stereo-coverage difficult to

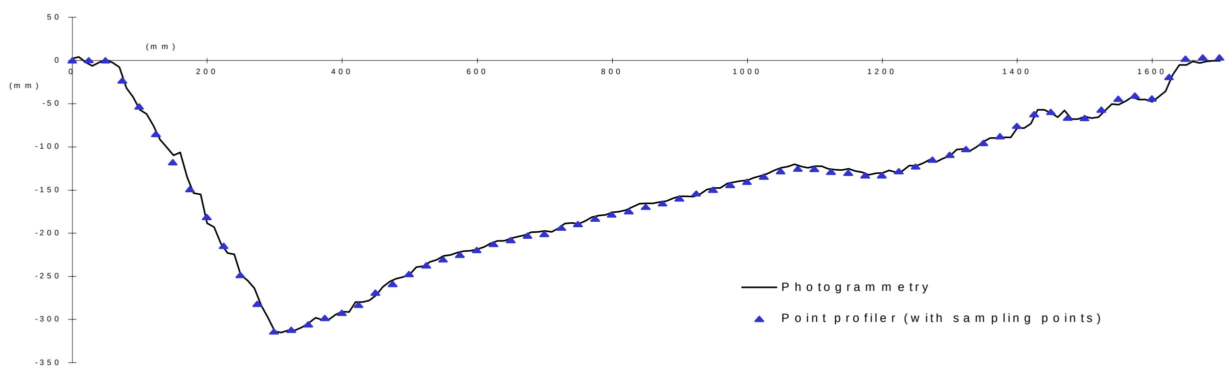

Figure 1, Accuracy of digital photogrammetry applied to the Flood Channel Facility (Camera Height = 4.2m) acquire at large-scale. The DCS460 was mounted using a simple scaffold plank with a 60mm diameter hole drilled for the camera lens, positioned on a moving overhead gantry 4.2m above the flume. The DCS460 was equipped with a 28mm lens so that the footprint of each frame was 4.1 x 2.8m. The difficult channel shape suggested that stereo coverage should be obtained in the form of discrete stereo-pairs rather than more conventional overlapping strips and 10 overlapping pairs were sufficient at the chosen photo-scale (1:150). Fifty conventional control targets were placed on the floodplain and channel sides and these points were again co-ordinated using theodolite intersection methods. The camera was calibrated using in-situ self-calibration methods (Chandler *et al.*, in press) and DEMs subsequently acquired (Chandler, *et al.*, 1998).

In order to quantify the accuracy of the generated DEMs, elevations were compared with those measured directly using a motorized profiling device (Wallingford, 1999) along several cross sections, (Figure 1). This figure suggests that correspondence is excellent, confirmed by summation of all discrepancies, which reveal that a r.m.s.e. accuracy of –1.9mm was achieved.

3.3 Loughborough Flume

The work on the large Flood Channel Facility (FCF) was replicated at one-quarter scale on a smaller flume based at Loughborough University, allowing greater variation of those fluvial parameters that influence process. One particular variable studied has been the impact of different depths of inundation (height above floodplain), with bedforms measured following each experiment (Figure 2). The importance of this work to the photogrammetric community is that the whole process has become a routine operation, completed in less than five hours. This includes image acquisition

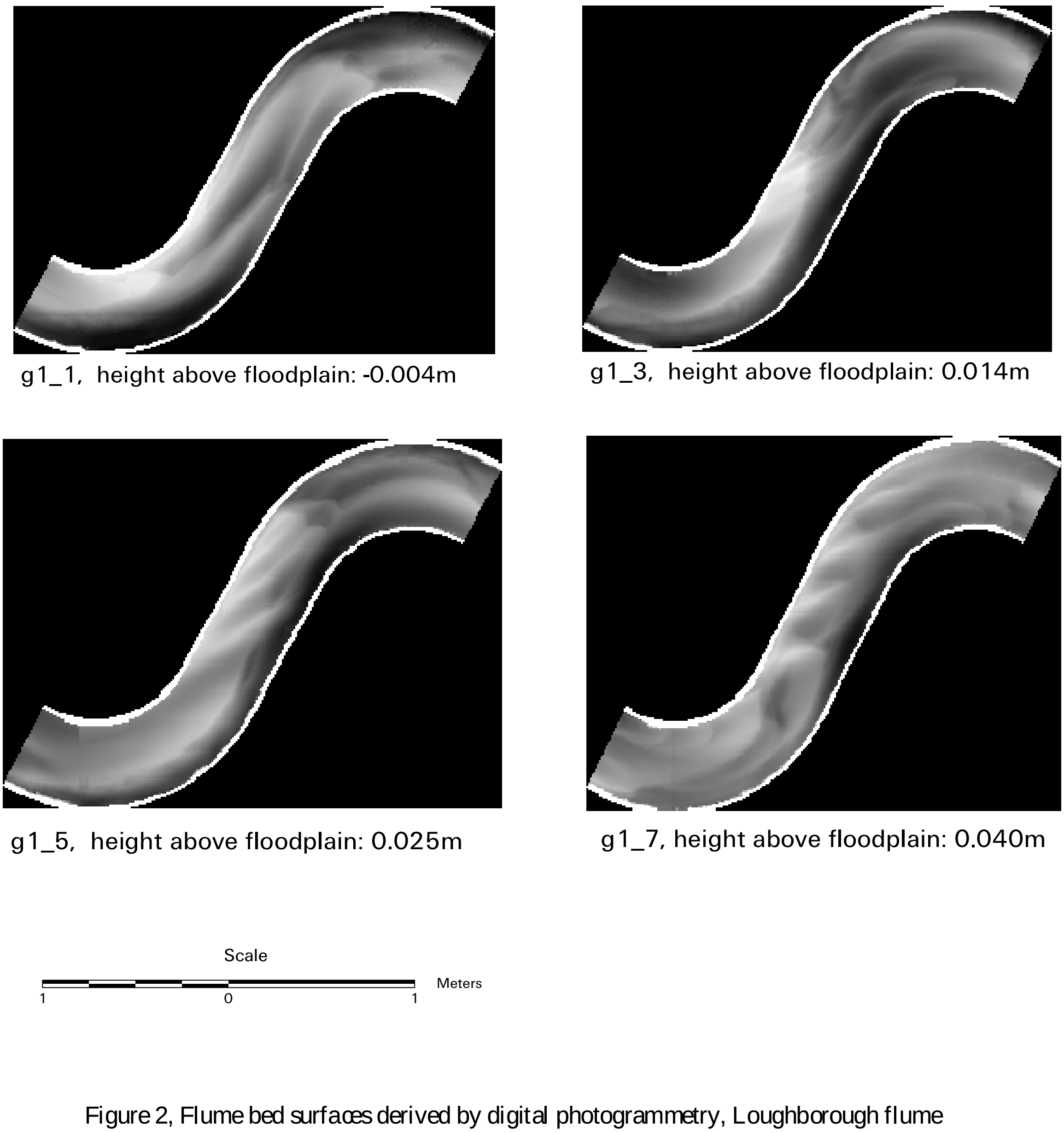

Figure 2, Flume bed surfaces derived by digital photogrammetry, Loughborough flume through to DEM creation and mosaicing and significantly, is being carried out by a competent fluvial researcher without any formal photogrammetric qualification or training. The system certainly demonstrates the value of a fluvial bed measurement system based upon digital photogrammetry and has become just another tool used by fluvial researchers.

3.4 Sunwapta River, Canadian Rockies

The projects reported upon above have all involved simulated river channel flumes, short camera-object distances (< 4.2m) and imagery acquired in the traditional vertical perspective. These are all situations where the photogrammetry can be planned, controlled and success would perhaps be expected. The final project was far more challenging, primarily because it involved measuring the changes occurring on a real river and required the use of oblique imagery at an approximate distance of 235m from the riverbed.

The Sunwapta River is a large and actively braiding, gravel-bed, pro-glacial river in the Rocky Mountains of Alberta, Canada, between Jasper and Lake Louise. The river is fed by the Athabasca Glacier and, due to the daily fluctuation in air temperatures, experiences low flows in the early morning, building to peak flows in the early evening. These variations are at a maximum during the summer meltwater period, when peak flows cause significant transport of bed sediment, causing substantial and rapid (daily) change in the streambed topography. Quantification of such changes can provide estimates of sediment transport rates (Lane *et al.*, 1995; Ashmore and Church, 1998). Automated DEM acquisition has been accomplished in flume studies for this purpose (Stojic *et al.*, 1998), but not in the field using oblique imagery. The low flows and exposed bed forms in the morning provide an opportunity to determine morphological change and to measure bedform by photogrammetric methods. It was accepted that traditional field survey methods would still be required to provide surface data beneath the low water surface, but it was hoped that the photogrammetry could reduce field survey time significantly and provide DEMs at high spatial and temporal densities.

Another unique attraction of the field site was the presence of a high cliff overlooking the reach, from which oblique and digital overlapping photographs could be obtained. This viewpoint had been used previously to obtain sequences of 35mm photography, to identify change by qualitative means (Goff and Ashmore, 1994). Images were obtained from 3 camera stations 45m apart; each was located 125m above and 235m from the center channel of the river. The Kodak DCS460 camera equipped with an 85mm lens was used, and combined coverage of two overlapping areas exceeded an area of the reach that was 125 long and 80m wide. Photo-scale varied, but in the centre of the reach was 1:2,750, with each pixel providing ground coverage of approximately 0.055 x 0.025m. Fifteen photo-control targets were placed upon prominent channel bars. These consisted of black and white painted boards with dimensions 0.3 x 0.3m, constructed locally and secured using steel reinforcing bars hammered into the stream bed. Their coordinates were derived by theodolite intersection methods using measurements obtained from three control stations. Average precision following a least squares variation of coordinates estimation was –5mm.

Digital photographs were obtained over a 13-day period in July/August 1999, initially at 9.00am in the morning but also at 7pm in the evening for the last four days of the monitoring phase. Images were downloaded, examined to assess/modify exposure settings and backed up on a portable PC each day. Additional bed monitoring was being carried out on a repeat daily basis by more conventional field surveying methods. This consisted of measuring 16 cross-stream profiles, each between 85m and 140m in length and 10m apart. The sampling strategy involved measuring points at intervals of one meter, with additional points introduced at significant breaks of slope and between these profile lines, and so approximately 3,000 points needed to be measured each day. Even with access to one motorized Total Station (Leica TCA1800) and four survey teams using levels and staffs, this occupied 4-5 hours of each field day, followed by 1-2hrs of data entry and processing each evening. In contrast, the

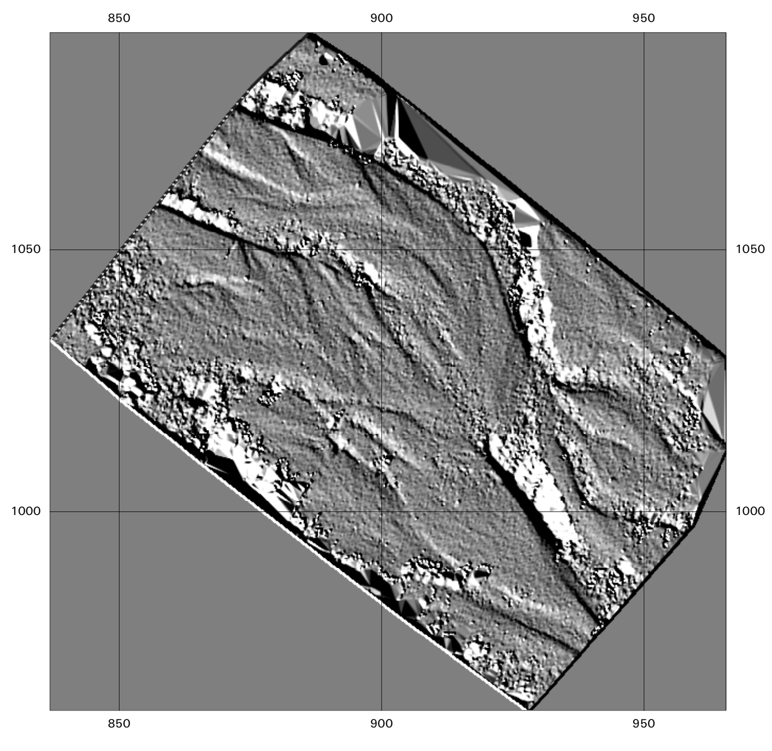

Figure 3, Slope shaded representation of DEM, Sunwapta- 30-07-99 time required to acquire imagery was just $1\frac{1}{2}$ hours, mostly taken by the time required to climb up to the camera stations.

Photogrammetric data processing was carried out back in the UK, using OrthoMAX to produce DEMs and OrthoBASE for orthophoto production. It is not possible for OrthoMAX to generate DEMs automatically from oblique imagery and using standard, documented procedures. However, previous research work (Pyle *et al*., 1997; Chandler, 1999) has shown that if the control is rotated so that the average vector between the two camera axes is near vertical, then it is possible to use the automated DEM extraction tools successfully. This strategy was adopted, and a reverse rotation applied to transform the automatically derived data back into the original coordinate system. DEMs were created at a resolution of 0.20m, for those days where change was experienced (Figure 3). Examination of the DEM, which consists of 250,000 points, reveals that the distinctive arcuate patterns within the bedforms are represented. These are consistent with the sequence of erosion and sediment deposition seen in flume experiments. It is also clear that small topographical features are represented, including minor bar-tops and channels. There are areas where inaccurate data has been generated, but these coincide with those regions inundated by flowing water at the time of photo-acquisition. Comparison of DEM elevations with heights extracted from the profiles measured by field survey reveal that the DEM accuracy is –0.044m, a satisfactory result considering that median grainsize was 0.04m and that ground coverage of each pixel was 0.025m or greater. Orthophotos (Figure 4) could be produced using the OrthoBASE product without recourse to rotating the control coordinates.

4 DISCUSSION

The practical work cited in section 3.0 demonstrates that digital photogrammetry can usefully be used to derive morphological data necessary to describe water worked surfaces. There are various controls upon the quality of such data.

The scale and configuration of the photographs acquired has a direct and highly predictable impact upon the precision of DEMs generated. One of the unique and well-known advantages of photogrammetry is the positive relationship between precision and photo-scale and this has again been illustrated during this study. Application of the methods for the Flood Channel Facility utilized a camera configuration that can be more efficient than the conventional 60% overlap and vertical imagery. The difficult sinusoidal wave shape of the FCF demanded a radical approach, with the most effective means of obtaining stereo-coverage being to obtain discrete overlapping stereo-pairs. Moreover, by orientating the axes of each camera slightly inwards, a 90-95% overlap can be achieved, again improving efficiency and ease of obtaining appropriate stereo coverage of complex objects.

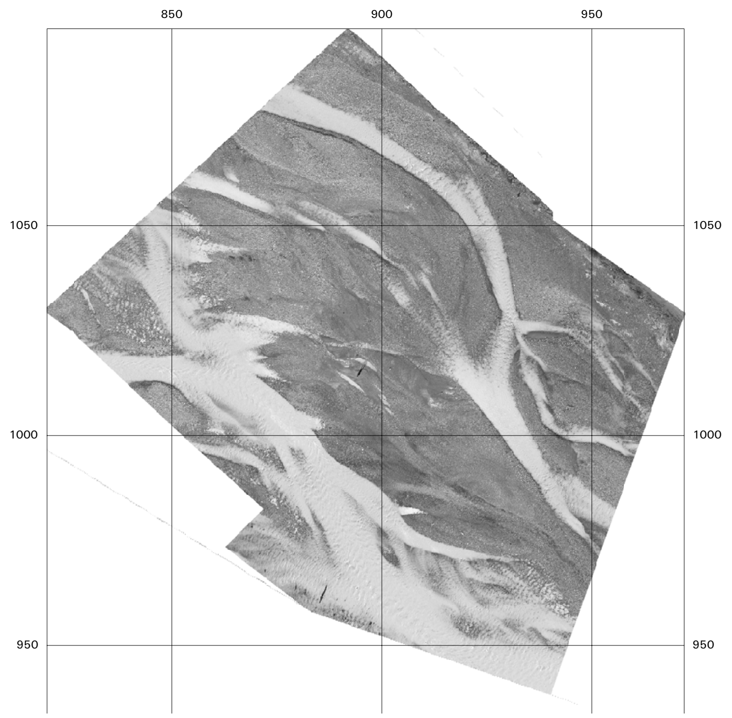

Figure 4, Orthophoto of braided system, Sunwapta- 30-07-99

Accurate camera calibration is clearly critical for deriving accurate DEMs, although the criticality of parameter groups used to model the inner geometry of the camera varies (Chandler *et al.,* in press). It has been found that it is particularly important to accurately model lens distortion, which arises from using the cheaper class of digital cameras designed for professional photography, rather than photogrammetry. Other parameters are less significant. Focal length and principal point offset, which can be important for convergent high precision networks used for deformation monitoring, were found to be insensitive to accuracy tests. It is suggested that for vertical imagery used to extract DEMs of surfaces which display minimal relief variation in relation to camera/object distance, that these two sets of parameters need to be estimated approximately only, (Chandler *et al*., in press).

It is pertinent to compare the accuracies achieved in the three cases, but particularly between the FCF and the Tilting flume, where accuracies are similar but the camera elevation was over twice as low. This paradox can be explained by considering the extent and likelihood of poor matching due to dead ground in regions between particles. The likelihood of dead ground is dependent upon the comparative size of the particles (median grain size) with the ground coverage of pixels comprising the images. In the FCF the median grainsize was 0.9mm and each pixel covered an area of 1.4mm, individual particles being difficult to discern. For the Tilting Flume, the median grain size was much larger (24mm) with each pixel occupying an area of just 0.6mm so that individual particles were clearly defined. The consequence of this variation is that for the Tilting flume, a large proportion of pixels lie in regions between particles and height estimates in these areas are unreliable because of the obstruction of light rays by adjacent particles. For the FCF study, median grainsize and pixel size is comparable and areas between particles are simply not represented in the imagery. It is important that careful attention must be given to the structure of the surface being studied and the relative size of pixel and particle size. Comparing the two studies has shown that accuracies are not directly dependent upon photo-scale. Reducing the camera elevation can *increase* the dead ground problem, which *decreases* surface accuracy.

One superficial conclusion from these studies would be that the surface aquired for the FCF is more accurate and therefore of greater value than the Tilting Flume DEM. In some respects this statement would be valid but this is a simplification. It would be more precise to state that the FCF surface is more accurate, provided that the desired surface is required to represent just the bedforms, (i.e. accurate at the bedform-scale). If the fluvial study required information regarding the composition and inter-relationships between the grains (i.e. information at the grain-scale) then the FCF surface must be considered inadequate. The Tilting flume DEM may be slightly inaccurate for those points between particles but it certainly contains information at the grainscale. The important conclusion is that the DEM must be generated at a resolution that is appropriate for the phenomena that are being investigated. It is interesting to note that this point is stated clearly by the Nyquist theorem (Graham, 1998) and although it's usage is well established amongst photogrammetrists for image acquisition, it is rarely used for considering generated data, such as a DEM.

In the case of the Sunwapta project, the image pixel size was similar to the median grainsize of the particles and the resolution of the extracted DEM was 0.20m. As the project desired spatial data at the bedform scale, both the pixel size and DEM resolution was appropriate for this scale of enquiry.

5 CONCLUSION

It has been shown that a measurement system based upon automated digital photogrammetry and a digital camera can be usefully used to measure the morphology of fluvially worked surfaces, both in a flume and in a real river. As expected, accuracies were found to be dependent upon normal photogrammetric controls such as scale, camera calibration and obliquity of view, but only partly. It has been shown also that the relative relationship between the size of the particles which constitute the bed and pixel dimensions on the object are critical. If the pixel size is larger than individual particles then the surface may be accurate at the bedform scale but will be inaccurate at the grainscale. The concept of different scales of representation is of great importance to the quality of any landform representation, it being essential for DEMs to be generated at a scale that is appropriate for the purposes intended.

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