Monitoring River-Channel Change Using Terrestrial Oblique Digital Imagery and Automated Digital Photogrammetry

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Imagery acquired using a high-resolution digital camera and ground survey has been used to monitor changes in bed topography and plan form, and to obtain synoptic water-surface and flow-depth information in the braided, gravel-bed Sunwapta River in the Canadian Rockies. Digital images were obtained during daily low flows during the summer meltwater season to maximize the exposed bed area and to map the water surface on the days with the highest flows. Images were acquired from a cliff-top 125 m above and at a distance of 235 m from the riverbed and used to generate high-resolution orthophotos and digital elevation models (DEMs) at a ground resolution of 0.2 m, within an area 80 × 125 m. The creation of DEMs from oblique and nonmetric imagery using automated digital photogrammetry can be difficult, but a solution based on rotation of coordinates is described here. Independent field verification demonstrated that root mean square accuracies of 0.045 m in elevation were achieved. The ground survey data representing riverbed topography were merged with photogrammetric DEMs of the exposed bars. The high-flow water surface could not be surveyed directly because wading was dangerous but was derived by ground survey of selected accessible points and photogrammetry. The DEMs and depth map provide high-resolution, continuous data on the channel morphology and will be the basis for subsequent two-dimensional flow-modeling of velocity and shear stress fields. The experience of using digital photogrammetry for monitoring river-channel change allows the authors to identify other potential benefits of using this technique for fluvial research and beyond. *Key Words: braided rivers, digital elevation models, sediment transport, spatial measurement.*

Physical geographers often need dense and accurate spatial data acquired through time to develop understanding and to assess the impact of earth surface processes, which inevitably creates a problem of spatial data acquisition. For example, fluvial geomorphologists interested in the short-term development of river morphology in relation to flow and sediment transport need topographic data but are then faced with onerous field-data collection needs. This is especially true of braided rivers, in which there has been a growing interest, partly because morphology changes rapidly enough to be observed on time scales of hours, days, or weeks. At the same time, the development of numerical simulations of river processes, the output from which is usually continuous (in time and space) information on flow depth, flow velocity, bed topography change, and bedload transport, has given impetus to efforts to collect comparable information in the field. Changes in bed topography may be particularly important because they provide data from which bed-load transport rate may be estimated (Goff and Ashmore 1994; Lane, Chandler, and Richards 1994; Ashmore and Church 1998). Collection of even basic data on river morphology by standard ground-survey methods has often occupied a large proportion of field time for fledgling fluvial researchers, to the point where it seems to be a rite of passage. While this may provide survey data for approximate estimation of morphology and morphological change, there is considerable interpolation involved in producing complete maps of the topography and planform. Digital photogrammetry using aerial photography may provide an alternative in some cases, but aerial surveys are not cheap to commission and repeat coverage at short time intervals is usually impossible. This article demonstrates that there is a low-cost alternative that may be appropriate: digital photogrammetry using oblique terrestrial imagery. This can solve many of the problems of inefficient data acquisition, although some ground survey may still be necessary. There is a substantial saving in cost, and the possibility exists of covering larger areas much more frequently than can be achieved with conventional surveying. It is important to recognize that although the case study focuses on fluvial research, the techniques described could equally be used to tackle morphological measurement problems in other areas of physical geography.

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Methods for Monitoring River-Channel Change

Monitoring river-channel change has traditionally involved the use of repeated leveling along regularly spaced cross-sections (e.g., Ashworth and Ferguson 1986; Ashmore et al. 1992; Warburton 1992). Such methods are time-consuming and, of course, provide no information about change occurring in areas between monitored sections, although estimates of erosion or deposition volumes may be possible by linear interpolation. More recently, Lane, Chandler, and Richards (1994) have demonstrated the value of combining different surveying techniques with digital terrain-modeling methods to quantify river-channel change. Lane and colleagues (1994) used analytical photogrammetry to monitor change in exposed areas and a Total Station to detect change occurring beneath the water surface, with all data measured in one single coordinate system. However, the work relied upon manual measurement methods, which can only generate a small sample of points on the surface. Lane (1998) discusses the issue of the quality of surface representation and naturally concludes that greater sampling density leads to improved surface quality.

Difficulties in acquiring field data on river dynamics have been circumvented to some extent by using small-scale physical models located in laboratories (e.g. Ashmore 1991; Hoey and Sutherland 1991; Young and Davies 1991), but the problem of acquiring high-resolution terrain data remains. In these environments, morphology was traditionally measured by the miniature equivalent of the surveyor's level and staff-manual point profilers. Automated versions are now available (Wallingford 1999), but data collection is still limited to one point every two to three seconds. Digital photogrammetry is much more efficient, because imagery can be acquired rapidly and subsequently dense digital elevation models (DEMs) can be obtained automatically at rates exceeding 100 points per second (Brunsden and Chandler 1996). Furthermore, processing overlapping stereo-pairs of vertical images is readily done with commercially available software packages (Erdas 1995). Stojic and colleagues (1998) demonstrated the value of this approach for quantifying morphological change occurring in a large (2.9×11.5 m) flume representing a braided channel system. From a strip of eight vertical photographs acquired using a Pentax 645 medium-format camera, DEMs consisting of 110,000 points were measured fully automatically. DEMs measured sequentially clearly quantified the pattern of topographic change over time, although the desired estimation of sediment transport rates proved more elusive. It was decided that this was due to poor description of the internal geometry of the nonphotogrammetric camera, which caused small but significant systematic inaccuracies that proved critical when quantifying small volumetric change.

The potential of automated digital photogrammetry for measuring water-worked sediments has been exploited and developed further. Chandler (1999) used the method to measure soil-surface changes induced by a rainfall simulator using an area-based matching method. Wolff and Förstner (2000) investigated the use of feature-based matching methods and multiple images to identify homologous points representing a migrating sand wave. Imagery was acquired during experimentation using a Perspex sheet to flatten the water surface. Such an approach avoids the need to drain the flume; Butler and colleagues (2002) developed a similar solution. Automated digital photogrammetry has become an accepted method used to measure water-worked flume surfaces and is now becoming routinely used by fluvial engineers (e.g., Rameshwaren et al. 1999; Chandler et al. 2001). However, these developments are restricted to application in an artificial laboratory environment, not the field environment, where other methods are also practicable.

Other Techniques

During the development of automated digital photogrammetry methods for fluvial geomorphology, other techniques have evolved that have also increased survey efficiency. Fully motorized Total Stations that track the prism are now available and can be used by a single person in the field. This increases data-acquisition rates enormously so that, depending on circumstances, it is possible to acquire in excess of 2,500 points per day to an accuracy of 10–20 mm. The Total Station is also versatile, allowing data to be measured under diverse sampling strategies and for points both above and below the water surface. Differential global positioning systems (GPS) (both standard and real-time) may give similar acquisition rates, but at lower precision and accuracy, particularly in elevation. Kinematic GPS methods allow even higher data-acquisition rates, though ensuring the verticality of antennae poles becomes a limiting factor on data accuracy. Airborne laser scanning (Lohr 1998) allows very dense DEMs to be generated and is widely used for flood-defense planning in the U.K. However, the cost of obtaining coverage is high for small areas, and data accuracy is constrained by limitations of differential GPS used to determine the position of the sensor. There is also some evidence that the quoted accuracy of 0.15 m is overly optimistic (Baltsavias 1999; Adams and Chandler 2002). Terrestrial laser scanning offers potential, but the technology is currently prohibitively expensive and is not ideally suited to the rigors of fieldwork. Photogrammetry is more versatile. Conventional photogrammetry using vertical aerial photography suffers from many of the limitations of airborne laser scanning because it is expensive to put any sensor in the sky. Despite this, and where finances allow, vertical aerial photography and automated digital photogrammetry provide a very flexible and efficient means of determining river-channel change, especially for large rivers (Lane 2000; Hicks et al. 2001). However, there are still limitations on vertical resolution and on repetition of surveys where successive changes need to be mapped frequently or on schedule. Oblique photography and videography has been used recently for descriptive analysis of braided river dynamics (Hicks et al. 2001), but this work does not extend to photogrammetric measurement and DEM extraction.

Automated digital photogrammetry using terrestrial oblique imagery appears to offer potential because of the decreasing cost of many digital cameras, because of the ease of obtaining ground-based photography, and because acquisition remains in the control of the user. It also makes close-range photography possible, giving improved resolution and therefore greater precision in the terrain data.

Despite these advantages, various practical problems need to be overcome. A suitable viewpoint must exist from which it is possible to acquire oblique photographs. Also, most commercial software used to generate DEMs automatically assumes that conventional vertical photography has been obtained, and therefore it may not work with oblique imagery. Finally, nonphotogrammetric digital cameras used for photo acquisition need to be calibrated if accurate data are to be generated (Kenefick, Gyer and Harp 1972; Fraser 1997).

Automated Digital Photogrammetry Using Oblique Imagery: Fieldwork

An opportunity to investigate the potential of using oblique image and automated digital photogrammetry for monitoring river-channel change became possible through collaboration between the universities of Western Ontario, Minnesota, Loughborough, and Genoa at a field site on the Sunwapta River site in the Canadian Rockies (Figure 1) in July and August 1999.

The Sunwapta Field Site

The Sunwapta River is a large and actively braiding, gravel-bed, proglacial river in the Rocky Mountains of Alberta, Canada, between Jasper and Lake Louise (Figure 1). The upstream reaches of the river are fed primarily by meltwater from the Columbia Icefield, particularly the Athabasca and Dome glaciers. Peak annual flows occur mid-July to mid-August during the peak of the glacier-melt season. At this time of year, the discharge follows a daily cycle driven by air temperature and solar radiation. Flow is lowest in the early morning and builds to a peak in the early evening. Successive days of high melt-rates cause flows to build, peaking higher and higher each day. The summer melt period is associated with significant transport of bed sediment, causing substantial and rapid (daily) change in the streambed topography (Goff and Ashmore 1994; Kussner 1995). The daily low flows expose large areas of bar surface and channels that are inundated at high flow, and this provided the opportunity to measure daily morphological change by photogrammetry while also making it possible to observe high-flow conditions within a few hours of low-flow surveys.

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, increase the study area, and provide DEMs at both high spatial and temporal densities. Further ground-survey data would be necessary to establish water-surface elevations, because it was not expected that the image-matching algorithm would be successful within flooded regions. The ground survey could also be extended to include profiles within the dry-bed areas, to provide accuracy checks on the photogrammetry.

The site was ideal because of the presence of a high cliff overlooking the reach from which oblique and digital overlapping photographs could be obtained. This viewpoint 125 m above the channel had been used previously to obtain sequences of 35-mm photography, to identify change by qualitative means (Goff and Ashmore 1994) and also to provide rectified photographs for mapping planform changes and aiding interpolation between surveyed cross-sections (Luce 1994; Kussner 1995). This site had the additional advantage of a Water Survey of Canada gauge at the upstream end of the reach, which operated between 1949 and 1997 and which could be recommissioned for the 1999 field season. This would provide flow records during the monitoring period, as well as historical information on discharge (Chew and Ashmore 2001).

Image Configuration

Digital images were obtained from three camera stations 45 m apart; each located 125 m above and 235 m from the center line of the main river channel (Figure 1). A Kodak DCS460 camera equipped with an 85-mm lens

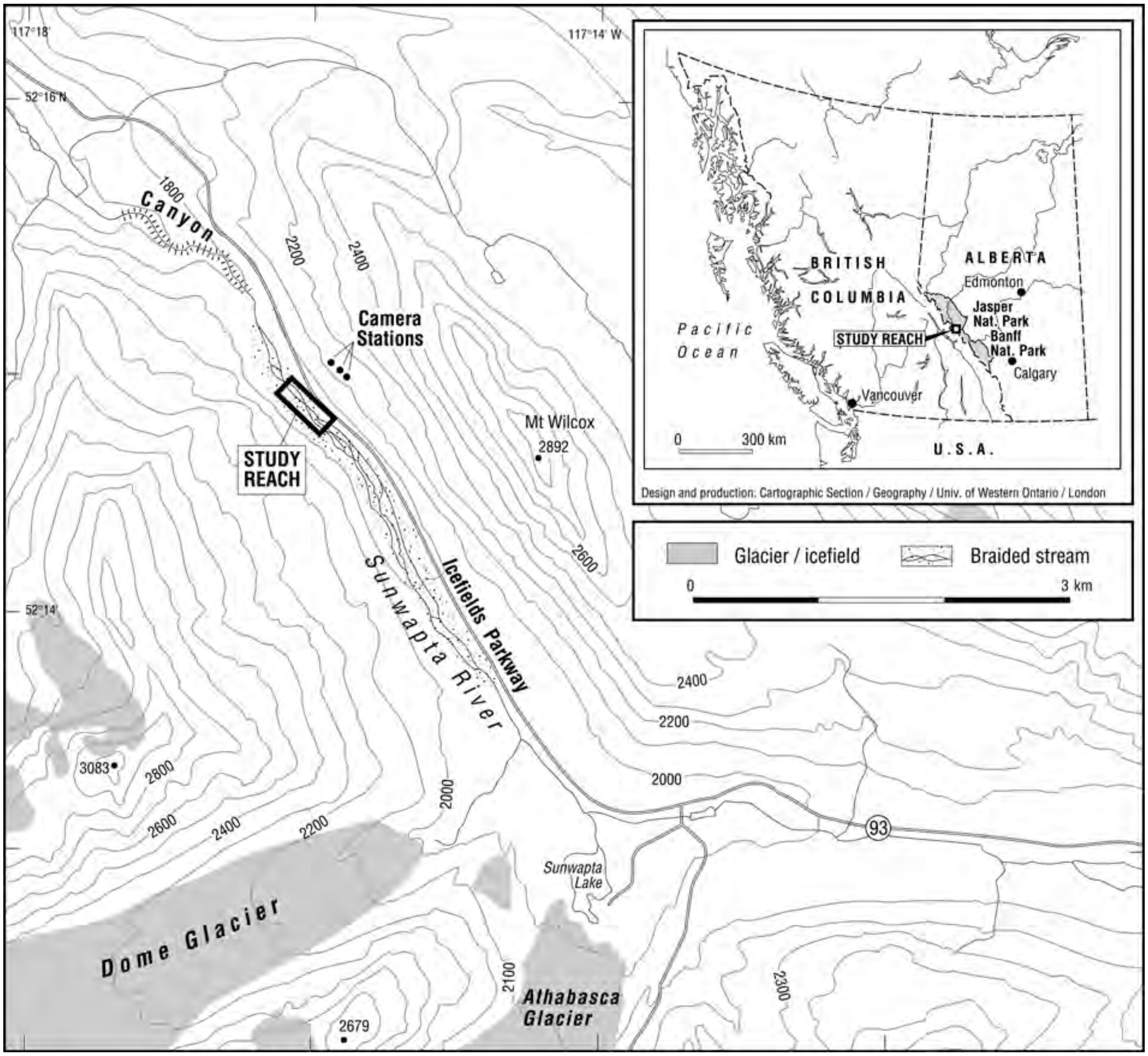

Figure 1. Location map showing field site and camera locations.

was used (Figure 2), and combined coverage of two overlapping areas covered an area of the reach that was 125 m long and 80 m wide. The Kodak DCS460 digital camera is not designed for photogrammetry but, if calibrated carefully, can be used successfully for photogrammetric measurement (Fraser 1997; Chandler et al. 2001). In order to minimize the impact of uncertain interior geometry, it was decided to permanently fix three tripods at the three camera stations (Figure 1). At the upstream and middle camera stations (Figure 2), two photographs were taken; one pointing towards the upstream area of the reach and the second towards the downstream area. This configuration provided appropriate stereo coverage for the desired site and also created the possibility of generating two DEMs for the downstream reach, derived from different stereo pairs. With this redundancy, the internal reliability of the DEM-generation process could be assessed, and there was a possibility that the accuracy could be improved by merging the two DEMs. Photo-scale varies across the image for oblique photographs but in the center of the reach was approximately 1:2,750; with each pixel providing ground coverage of approximately 0.055×0.025 m. This size-range is close to the average particle size of the gravel within the riverbed.

Control Configuration

Fifteen photo-control targets were placed upon prominent channel bars distributed throughout the reach. These consisted of black-and-white-painted boards with dimensions 0.3×0.3 m, constructed locally and secured

Figure 2. Camera station showing fixed camera tripod and field site.

Figure 3. Control targets on channel bars.

using steel reinforcing bars hammered into the streambed (Figure 3). The minimum number of control targets necessary is strictly only four per stereo pair, but it is prudent to install additional targets, particularly in an active braided river, where boards may be washed or eroded away during high flows. Additional redundant control also improves both the precision and the reliability of the photogrammetric restitution. The coordinates of the photo-control targets were established by measuring vertical and horizontal angles using a Total Station located at three control stations on stable ground. Measurements and slope distances between the control stations were combined in a least-squares "variation of coordinates" estimation program. Precision of each control point was approximately ±5 mm.

Monitoring Strategy

Digital photographs were obtained over a thirteen-day period in July and August 1999, initially at 9:00 a.m. but also at 7:00 p.m. for the last four days of the monitoring phase. One of the advantages of using a digital camera was that images were downloaded immediately and examined to assess whether exposure settings were appropriate. All images were also copied and backed up onto a portable PC each day. Additional bed-monitoring was carried out on a repeat daily basis by more conventional field-surveying methods. This consisted of measuring sixteen cross-stream profiles, each between 85 m and 140 m in length and 10 m apart (Figure 4). The sampling strategy involved measuring points at intervals of one meter along fixed survey lines, with additional points introduced at significant breaks of slope, and so approximately 2,000 points needed to be measured each day. Additional points, typically 1,500–2,000, were added between cross-sections in submerged areas, to improve interpolation between cross-sections. Even with access to both a standard and motorized Total Station (Leica TCA1800) and four survey teams (eight to ten people total) using levels and staffs, this occupied four to five hours, followed by one to two hours of data entry and processing each day. In contrast, the imagery could be acquired by one person in just one and a half hours, mostly taken by the time required to climb up to the camera stations and back, demonstrating the potentially very large savings in field time and personnel. On the four days for which evening high-flow images were taken, the team also surveyed the water-surface elevation on the ground using the Total Station. This survey consisted of approximately 300 points distributed along the edge of the water or within the midchannel where bars emerged above the flow.

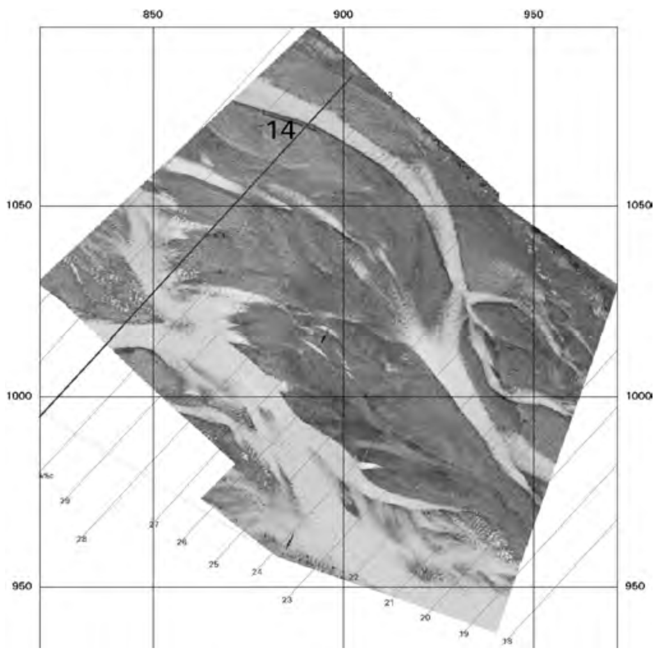

Figure 4. Orthophotograph representing full reach and positions of check profiles.

Automated Digital Photogrammetry Using Oblique Imagery: Data-Processing

Readers seeking full explanations of the photogrammetric data processing should consult one of the many textbooks on photogrammetry (e.g., Greve 1996; Wolf and Dewitt 2000; Mikhail, Bethel, and McGlone 2001) or perhaps consult relevant software manuals. The focus here is on the novel aspects of the data-processing steps used in this study and the characteristics of the resulting data.

Two distinct products can be generated by photogrammetry, both of value to geomorphology and fluvial engineers. Of key significance is the DEM, which represents the three-dimensional shape, or morphology, of the site. The automation of this measurement procedure is really the main reason for adopting a digital photogrammetric solution and provides a very dense sample in the form of a regular grid of points. The density of this grid is user-definable and can be sufficiently high to avoid the need to measure break lines explicitly, which are a necessity when using lower-resolution acquisition methods (Lane 1998). The second product is the orthophotograph, which appears similar to a vertical aerial photograph but, because distortions due to relief and photo-tilt have been removed, has the metric qualities of a true map (Greve 1996).

Access to appropriate software is required to generate both DEMs and orthophotographs, and there is great competition among software vendors. Some commercial packages focus on traditional photogrammetric markets involving map production (e.g., LH-systems, Z/I Imaging, DAT/EM, Virtuozo), while other vendors have aimed their products at the potentially larger markets associated with geographic information systems (GIS) and remote sensing (e.g., Erdas, DVP-GS, PCI Easi/Pace). One vendor that has been particularly attractive to the U.K. research community has been Erdas, because a Combined Higher Education Software Team (CHEST) software arrangement provides cheap access to their software. Originally the key Erdas package was OrthoMax, which allowed the generation of both DEMs and orthophotographs from vertical aerial photography. It did not support oblique imagery. OrthoBase, a more recent Erdas product, currently allows orthophotographs to be generated from oblique and vertical imagery. It does not support the automatic creation of DEMs, although this is planned (Chandler 1999) and is being developed. Indeed, in September 2001 the first author of this article successfully examined a beta-test version of OrthoBase Professional.

At the time that the data in this article were processed, the only option available involved using OrthoBase to generate the orthophotographs and to adapt the data-processing strategy of OrthoMax to generate DEMs automatically from the oblique imagery.

DEM Generation

The initial phase of data-processing was routine and involved downloading and then measuring the image locations of the photo-control targets appearing on the five images at each epoch. Once these were measured, it was possible to estimate the positions and orientation of all five photographs in the original coordinate system, a process known as deriving the "exterior orientation" (Mikhail, Bethel, and McGlone 2001, 90). The bundle-adjustment software within OrthoMax is capable of carrying out such a restitution using oblique images, although initial values for the exterior orientation parameters need to be provided. An additional phase of work that was not a standardized procedure was to establish the inner camera geometry; principally determining the camera focal length and a lens-distortion model. This was achieved using the measured-image and object-control coordinates, utilizing an external self-calibrating bundle adjustment and procedures that have been well documented (Chandler 1999; Chandler et al. 2001). Once the inner camera geometry had been determined, the relevant parameters were entered into the OrthoMax software and the bundle adjustment rerun to establish the final exterior orientation parameters for each photograph.

Once the final position and rotation parameters (i.e., exterior orientation) have been established, it is normal practice to generate DEMs automatically. Unfortunately, if this is attempted for photographs where the rotations are greater than 5–10° (i.e., oblique imagery), then the DEM generation process is unsuccessful in OrthoMax. Internally, the algorithm assumes that depth perception or x-parallax (Mikhail, Bethel, and McGlone 2001) is aligned to the Z-axis of the object coordinate system, which is not the case for oblique imagery. A simple solution, previously developed and tested on two small-scale applications (Pyle, Richards, and Chandler 1997; Chandler 1999), involves rotating the object coordinate system so that the mean camera axis for the desired photo-pair is approximately vertical (Chandler 1999). The automatic DEM generation procedure is then carried out, creating points representing the object in a rotated coordinate system. The rotation is then reversed, transforming the extracted points back into the original coordinate system. This approach was adopted successfully in this project, although a small modification was included to eliminate erroneous heights generated within areas inundated by water. Such false matches were expected, and erroneous values were removed by checking whether point elevations were within an expected range, this being determined by field measurement. The procedure was repeated for the adjacent stereopair at each desired epoch, and both were merged and combined using the Erdas Imagine mosaiking tool, to create a dense DEM representing the whole dry part of the reach at a particular time and date (Figure 5).

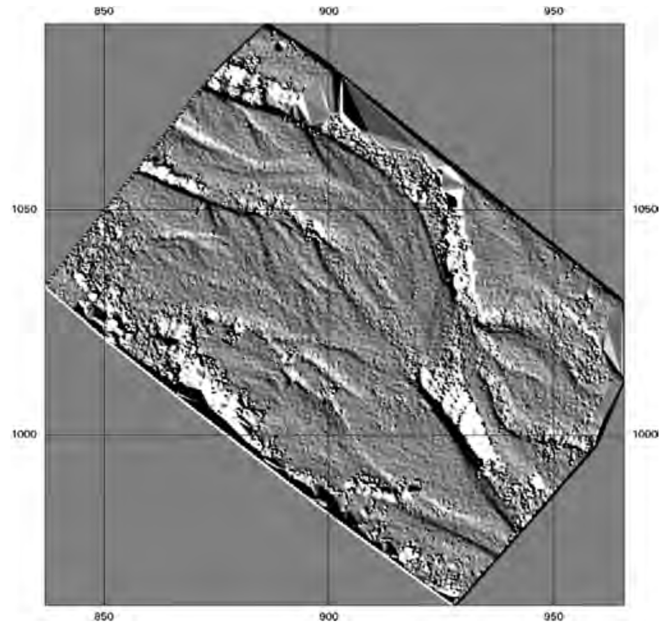

Figure 5. Slope-shaded representation of DEM of whole reach.

Orthophotograph Generation

The creation of orthophotographs at each epoch was a comparatively routine procedure using OrthoBase, primarily because the software is designed for use with both vertical and oblique imagery. An orthophotograph is generated by transforming the source image into an orthographic projection while removing the distortions arising from relief displacement. It was again necessary to measure the image locations of all control points on the images and carry out a bundle adjustment to establish the position and orientation of all photos, as performed for the DEM generation procedure. To generate the most accurate orthophotographs, it is essential to stipulate a surface model to eradicate distortions due to relief displacement, although in OrthoBase it is possible to stipulate an assumed plane. Clearly, in this project it was possible to specify the DEM that had been generated earlier. The procedure was again repeated for two of the five frames, and the two orthophotographs were joined using the Erdas Imagine mosaiking tool, to provide a single orthophotograph of the full reach (Figure 4). The position of the photo sites relative to the river, and the focal length of the camera lens, precluded photogrammetric coverage of the entire width of the river but did include both of the major channels and most of the areas where channel changes occurred.

Quality of Data Generated by Automated Digital Photogrammetry Using Oblique Imagery

When considering the quality of data derived by surveying and photogrammetry, it is customary to consider three distinct aspects and to relate these to three sources of error (Cooper 1987; Cooper and Cross 1991). Precision is a measure of random errors, accuracy is a measure of systematic errors, and reliability is related to the ability to detect gross errors (internal reliability) and measure their effects upon derived data (external reliability) (Cooper and Cross 1991).

The precision of derived data is controlled by the precision of the photo-measurements and the scale and geometry of the photogrammetric network. Measures of precision are simple to derive, because the covariance matrix is a byproduct of the least-squares bundle adjustment used to relate image to object. If the precision of both the measured photo-coordinates and the control points are judged appropriate, then the diagonal elements

Table 1. Variation of Precision with Position

Position	X	Y	Z
Foreground, 205 m from cameras	±0.007 m	±0.013 m	±0.012 m
Background, 280 m from cameras	±0.020 m	±0.026 m	±0.018 m

of the covariance matrix represent variances for all estimated parameters, including object point coordinates. The coordinate estimates determined by automatic DEM generation procedures are obtained from a pair of images, so the precision of the DEM can be obtained by processing the relevant stereo pair in a bundle adjustment. This procedure was carried out for the Sunwapta site, and Table 1 conveys how the precision varies with position relative to the camera stations. As expected, the precision of object coordinates decays with increasing distance from the cameras.

The internal reliability of the DEMs can be assessed by comparing elevation estimates for the same point derived from overlapping DEMs (Pyle, Richards, and Chandler 1997) and this approach was carried out for one epoch of the Sunwapta data. An average difference of +0.029 m (standard deviation of ±0.094 m) was computed, although this includes some gross errors arising from flooded areas. The number of points used in this computation was 1,400, a large sample.

Intuitively, the most understandable and therefore useful measure of data quality is accuracy, which can only be assessed by comparing measured data with checkpoints established by independent and accepted methods. In this study, independent check data were available in the form of cross-sections surveyed primarily to determine streambed elevations beneath the water surface (Figure 4). These redundant data therefore provided perfect independent checkpoints necessary to establish the genuine accuracy of the photogrammetric data. Figure 6 conveys the elevation differences between level and photogrammetric data for the same profile (profile no. 14, Figure 4), and initial appraisal suggests that there is some variation. Closer examination reveals that excessive differences only occur where the channel is flooded, and where the bed is dry correspondence is good. Further analysis based upon all cross-sections measured on two separate dates (Table 2, "Single DEM, raw data with no merge") confirms that the overall root mean square error (RMSE) difference was 0.047 m and 0.044 m on 4 and 8 August respectively. This represents a very satisfactory outcome, considering that the median grain size was 0.04 m and ground coverage occupied by each pixel was 0.025 m or greater. Furthermore, the true accuracy of the leveling profiles used as "check data" has to be considered. For example, the uncertainty in identifying and locating breaks in slope is estimated to be ±0.05 m in plan, possibly ±0.03 m in height.

Improving Data Accuracy through Merging Overlapping DEMs

Table 2 also demonstrates that data of even higher accuracy could be obtained by using an intelligent merge using a Failure Warning Model. This arose from a desire to establish whether it was possible to increase accuracies by merging two DEMs representing the same area, but obtained using different imagery. The image configuration had deliberately included images in addition to the basic stereo coverage necessary for DEM creation, with

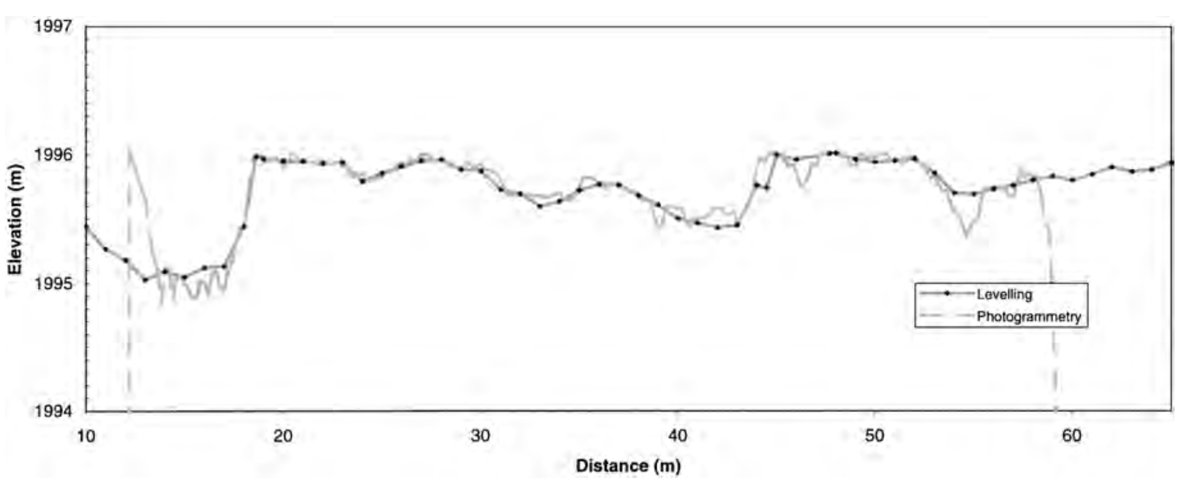

Figure 6. Comparative profile (no. 14) derived by photogrammetry and field-leveling.

Table 2. Accuracy of Automated DEM Generation in Dry-Bed Areas

RMSE Derived from 41 Check Points along 5 Profiles	4 August	8 August
Single DEM, raw data with no merge	0.047 m	0.044 m
Intelligent merging of two DEMs using "Failure Warning Model"	0.038 m	0.031 m

photographs covering the downstream reach obtained from all three camera stations. This redundant design made it possible to create two DEMs of this area, using imagery acquired from the upper and middle camera stations and the middle and lower camera stations. The obvious way to merge these two DEMs involved simply averaging the two elevation estimates for any particular point location. This approach was adopted initially, but independent accuracy assessments showed a degradation in accuracy. Investigation revealed that simple averaging of the two height values took no account of matching success of individual points, it being possible for an accurate height in one DEM to be corrupted by averaging with an inaccurate height derived from the second DEM. It was thought that this process could account for the reduction in accuracy that was apparent, and a more sophisticated and successful merging method was sought.

Recent research has assessed the significance of the DEM strategy parameters on the reliability of automatically generated DEMs (Gooch and Chandler 1998; Gooch, Chandler, and Stojic 1999). One development was the "Failure Warning Model" (FWM), which is able to classify the reliability of the estimated elevations within a DEM (Fox and Gooch 2001; Gooch and Chandler 2001). The FWM achieves this by making use of two DEMs generated from a single stereo pair, each generated using slightly differing strategy parameters. Detailed tests had revealed that accurately correlated points are not susceptible to strategy-parameter changes, while points poorly suited to image-correlation methods are sensitive to the strategy parameters (Gooch and Chandler 2001). Furthermore, these tests demonstrated that this approach is far more useful than relying upon the internal classification provided by the Erdas software, because false and therefore inaccurate matches are often classified as good. An algorithm was developed in the form of an "Erdas Graphical Model," which incorporates the FWM as a basis for merging the two overlapping DEMs. For each spatial point, if the FWM decides that both data sources are reliable, then a simple averaging method is judged appropriate. If only one of the two height estimates is judged reliable, then the final estimate is derived from the reliable source. If both height estimates are unreliable, then a zero height is assigned, to signify that no valid height could be determined. The accuracy of the algorithm, tested using overlapping DEMs derived at two separate dates (Table 2), demonstrates that an intelligent merge using the FWM improved the accuracy significantly, between 20 and 30 percent.

Application to Fluvial Morphology and Hydraulics

The purpose of the photogrammetric work was to assess its utility as part of a scheme for acquiring complete maps of riverbed topography and flow depth for each day and for measuring topographic change from day to day. The photogrammetry was used to produce DEMs of the whole riverbed, but inevitably included erroneous surface estimates in the wetted areas. An additional 1,000–1,500 survey points had been obtained at low flow, to measure the cross-sections and obtain data points distributed beneath the water surface. This ground-survey dataset was interpolated into a 0.5-m gridded DEM using the Surfer 7® terrain-analysis software package; an inverse distance-weighted interpolation algorithm was used with a weighting power of 2, smoothing factor of 10, and an anisotropy ratio of 1.5.

DEMs representing the whole channel-bed surface for each day were then created by replacing the inaccurate water-surface data within the photogrammetric DEM with the interpolated ground-survey dataset, using the water edge defined by the orthophotographs as the boundary between the two DEMs (Figure 7A–C). Merging the DEMs presented some minor problems, particularly at the water margins, where the photogrammetric data was sometimes of poor quality because such boundary points were influenced by poor image-matching on the adjacent water surface. These difficulties were compounded by photogrammetric inaccuracies arising from features obscuring the sometimes steep bank points; the well-known "dead ground" issue (Wolf and Dewitt 2000).

The real benefit of the photogrammetric approach is the provision of elevation data for large expanses of the riverbed exposed at low flow, and this obviously has the potential to save a large amount of time and effort in carrying out ground surveys. The relative proportions of wet and dry areas varied from day to day, but the dry areas represented more than half of the total surveyed area, even on the days with the highest flows of the year. The variation in daily flow causes a large part of the dry area at low flow to be underwater during the daily flow peak. This stage-dependent wetted area was about 20

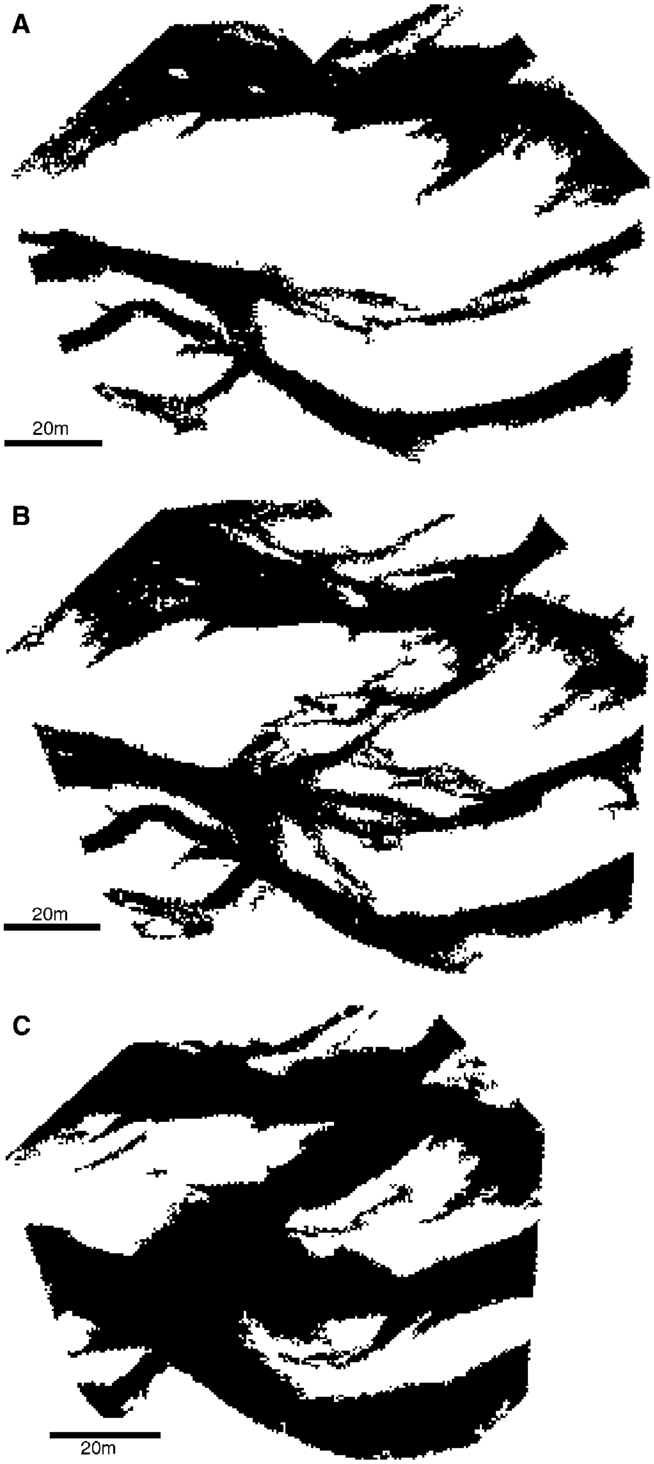

Figure 7. Variation in flow coverage: (A) 6 August a.m., (B) 7 August a.m., (C) 7 August p.m.

percent of the total area on most days. If the channels had undergone substantial migration or avulsion, this stage-dependent wetted area would have been much larger, thereby allowing the photogrammetric DEM creation approach to be even more valuable.

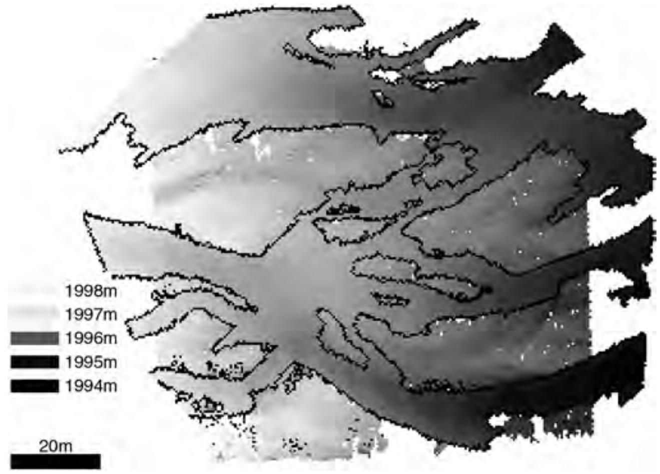

Figure 8. Merged DEM: dry- and wet-bed, 7 August.

The merged DEM shows substantial differences between the two sources of data (Figure 8). The in-channel-bed topography, interpolated from ground surveys, shows a general, smoothed picture of the major topographic variations. In contrast, the photogrammetric DEM gives a much more detailed and textured image of the terrain, allowing small-scale terrain measurements to be matched exactly with the orthophotographs (Figure 4). This enables terrain to be related to the details of the grain sizes and sedimentary or erosional features. DEMs of difference (Figure 9) should reveal detail of elevation change at the same spatial resolution as the DEMs. However, in this case they do not because dry-bed areas are generally regions exhibiting minimal change in topography, with most changes in topography occurring in the channels. One of the frustrations with this particular fieldwork season was that, unusually, there was no sustained period of hot weather, causing a major catastrophic flow event

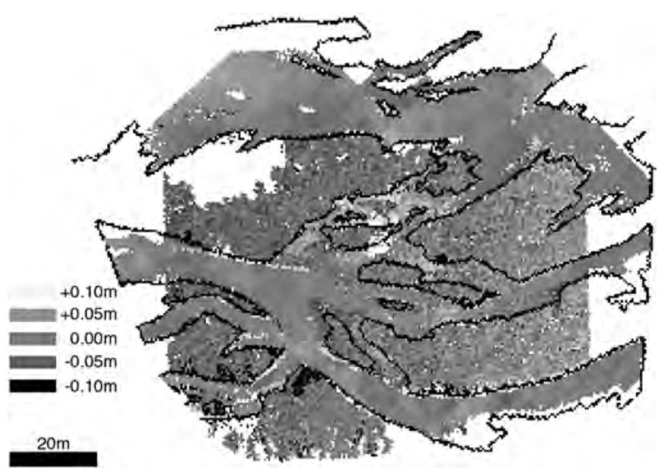

Figure 9. DEM of difference: 6–7 August.

that markedly modified channel geometry. However, in such cases where substantial change occurs, such as lateral migration of channels or channel avulsion, the photogrammetric DEMs would obviously have the potential to yield a detailed picture of topographic change by resolving terrain details at low flow on successive days.

One possible shortcoming of the approach is that there may also be substantial areas for which the terrain is acquired by different survey methods on different days, so that some spatial and temporal variation may be introduced in the quality of the DEMs. Theories underlying detection of morphological change distinguish between "discrepancies" and "significant movements" (Cooper 1987, 339) and only if coordinate differences are greater than the square root of the sum of the variances scaled by an appropriate level of statistical confidence is genuine change acknowledged. It is therefore important to quantify the precision of the DEMs representing the surface at the two epochs, which can be achieved using proper photogrammetric and survey design procedures in any proposed measurement scenario.

The high-flow water surface and flow depth were reconstructed for the four days on which evening high-flow photos and water-surface surveys were available (Figure 10). The images were orthorectified, using the low-flow DEM, to provide accurate maps of the extent of the wetted area and to aid in interpreting the ground-survey points. The water surface was interpolated from the ground-survey points using a gridded triangulated irregular network (TIN) from which the dry areas were then masked out. After checking for artifacts, the high-flow water surface was then combined with the low-flow topography from earlier the same day to produce a flow-depth map for the high-flow conditions. Direct measurement of depths at high flow is impossible, because the depth and velocity of the water at high flow precludes wading in many areas of the river. The photogrammetry provides a very convenient orthophoto map of the high-flow water surface to aid interpretation, and if linked to the DEM, provides much of the bed topography for the water-depth map. The continuous depth data make it very easy to see the main flow paths and details of local variation in depth.

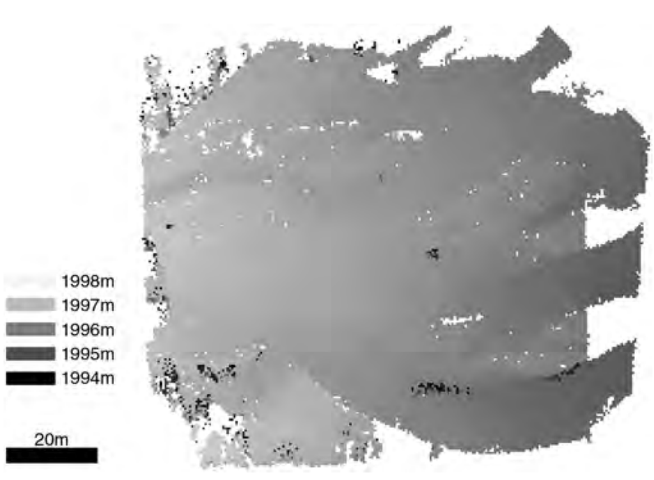

Figure 10. Merged DEM: dry-bed and water-surface, 7 August.

The photogrammetry is valuable in producing both spectral and morphological data. The spectral orthophotographs are an extremely efficient method for mapping planform and distinguishing between wet and dry areas of the channel. The photogrammetric DEM data describes morphology and can cover large areas of the bed at low flow in this type of channel. This potentially offers substantial time savings in the field, along with a density of topographic detail that can never be obtained from interpolation of ground-survey points.

Potential Uses of Oblique Photogrammetric Data in Fluvial Research and Hydraulics

The study has demonstrated the value of the oblique photogrammetry data in obtaining high-resolution, continuous, terrain, and flow data in the field, though it is true that one of the major strengths of the field site chosen was the availability of the high cliff overlooking the river reach, which provided an ideal vantage point for photo acquisition. Oblique photogrammetry is certainly not practicable in all situations, but there is no fixed threshold at which imagery becomes too oblique to use; neither is there an upper limit on the distance between camera and object. The basic constraint is that the object of interest must appear on a minimum of two images, and the incidence of objects in the foreground obscuring required points in the distance (the dead-ground problem) clearly increases as the angle of the obliquity reduces. Scale and geometric constraints are directly related to the desired precision of data required; once this has been defined, an appropriate configuration that incorporates variables such as camera, CCD (charge-coupled-device) resolution, lenses, and camera-station location and availability can be designed.

Following appropriate photogrammetric design procedures and competent fieldwork, this study has shown that photogrammetric data can be obtained rapidly, cheaply, at any temporal frequency, and at close range (large-scale), all under the direct control of the researcher on the ground. Dynamic gravel-bed rivers are often situated in steep-sided river valleys where locations for acquiring oblique photographs may well exist. In other cases, artificial vantage points may also be used, including low-altitude aerial platforms. The general approach is obviously applicable to a variety of landforms and processes other than rivers, especially where measurement of rapid topographic change or of conditions at a specific time are needed with a precision down to the order of 0.01 m. There are many possible uses of such photogrammetric data, whether acquired using oblique or, indeed, vertical aerial photographs. In the case described here they include:

- *Description and mapping of planimetric changes from orthophotographs.* The analysis of channel dynamics requires a long-term record of morphological change. Planimetric change alone can reveal important information about processes such as confluence-diffluence dynamics and rates of bar migration or bank retreat. These have been studied in small-scale physical models, but so far we lack sufficiently long records from the field (where the time scale of changes is much larger than physical models) against which to check model observations, or the equivalent information from numerical simulations. Continuous (or high-frequency) monitoring from the air is impossible. Terrestrial photogrammetry, given a suitable site, yields high-resolution orthophotographs and is clearly a very promising option for accurate, high-frequency measurements of planform compared to the treadmill of frequent ground surveys that, in any case, can never offer the interpretive detail of photographs. Accurate orthophotographs require a DEM in order to correct for distortions due to relief variation; the work reported here demonstrates that this is feasible with existing commercial software and suitable stereo digital photography. Other authors have shown that analysis can be extended to derive information on grain-size variation across bar surfaces (Butler, Lane, and Chandler 2001) and this could be extended through time because of the large photoscale that is possible with terrestrial photographs. The orthophotographs also provide a ready and very accurate source of data on wetted area, average flow width, and channel network properties at a range of flow stages, which may be useful in hydraulic research and in other geomorphic and habitat studies.
- *Bed kinetics.* Rates of change of bed elevation and the frequency distribution and spatial pattern of scour and fill are fundamental characteristics of fluvial processes. This information is used in assessment of channel processes, in estimating bed-material transport rates, and in fish-habitat studies (e.g., egg survival during scour by flood flows). Models and predictions of scour depth and the active bed area are still rudimentary and often based on limited direct-point measurements. Photogrammetry can help to provide continuous data—at least for some parts of the riverbed—to increase the sample size, improve the knowledge of spatial patterns, and reduce the reliance on interpolated point data.
- *Calculation of volumes of sediment transport.* Budget-based estimates of downstream variation of bed-material transport rates (Ashmore and Church 1998) require accurate measurements of volumes of change. Ideally, this requires vertical resolution of the order of the median grain size combined with high spatial density of points. This is possible with the close-range terrestrial photogrammetry described here. In many rivers, large areas of the bed are exposed at low flow between transport events; photogrammetric coverage of these areas reduces the time and effort in the field and allows ground surveying to focus on submerged areas.
- *Synoptic flow data.* Both the orthophotographs and the DEMs generated from oblique photogrammetry are necessary input for deriving maps of flow depth and width. These continuous (spatial) data can be used to provide spatial patterns of flow and statistics of variations at any flow stage for which the data are collected. Photogrammetry makes it possible to acquire some of this data simultaneously over a wide area, avoiding problems of stage changes during measurement.
- *Input for flow modeling velocity, shear stress, hydraulic roughness and sediment transport.* The bed-topography and water-surface data can provide detailed, synoptic input to computational flow models from which local velocity, hydraulic roughness, and shear stress fields may be derived. These may then form the basis for calculation of local bed-material mobility and transport rates. The measured flow depths and water-surface maps provide some verification of results.
- *Combined topography and grain size maps.* The high-resolution orthophotographs give details on bar and channel morphology and can also be used to derive maps of grain size or bed texture. Draping these over the bed topography will allow for spatial mapping of sediment texture in relation to bar topography and elevation. Combined topography and grain-size data goes a long way towards describing the sedimentology of the river deposits and the development over time. In hydraulics and sediment transport, the spatial distribution of grain size in relation to bed topography could be extremely valuable in modeling.

Conclusion

The work in this article demonstrates the value of oblique digital imagery combined with automated digital photogrammetry for monitoring planform, topography, and rates of change in braided river channels and as input to computational flow models. The one-day symposium recently organized by the Photogrammetric Society and the British Geomorphological Research Group (2001) demonstrated the important role that photogrammetry is beginning to play in geomorphology. Many of the projects reported utilized simple vertical aerial photography and standard photogrammetric procedures. This project has demonstrated that it is possible to extend the capabilities of standard photogrammetry to incorporate nonmetric and oblique imagery and therefore to develop a cheaper, more versatile measurement system capable of generating data of appropriate quality for fluvial research and beyond.

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