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DEVELOPMENTS IN MONITORING AND MODELLING SMALL-SCALE RIVER BED TOPOGRAPHY

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ABSTRACT

Recent research in fluvial geomorphology has emphasized the spatially distributed feedbacks amongst river channel topography, flow hydraulics and sediment transport. Although understanding of the behaviour of dynamic river channels has been increased markedly through detailed within-channel process studies, less attention has been given to the accurate monitoring and terrain modelling of river channel form using three-dimensional measurements. However, such information is useful in two distinct senses. Firstly, it is one of the necessary boundary conditions for a physically based, deterministic modelling approach in which three-dimensional topography and river discharge drive within-channel flow hydraulics and ultimately spatial patterns of erosion and deposition and therefore channel change. Secondly, research has shown that an alternative means of estimating the medium-term bedload transport rate can be based upon monitoring spatial patterns of erosion and deposition within the river channel. This paper presents a detailed assessment of the distributed monitoring and terrain modelling of river bed topography using a technique that combines rigorous analytical photogrammetry with rapid ground survey. The availability of increasingly sophisticated terrain modelling packages developed for civil engineering application allows the representation of topographic information as a landform surface. Intercomparison of landform surfaces allows visualization and quantification of spatial patterns of erosion and deposition. A detailed assessment is undertaken of the quality of the morphological information acquired. This allow some general comments to be made concerning the use of more traditional methods to monitor and represent small-scale river channel morphology.

KEY WORDS Digital terrain models Photogrammetry Braided rivers River dynamics

INTRODUCTION

One of the legacies of hydraulic geometry is that much of the information that provides the basis for current analysis of river channel morphology is provided by monitoring one or a number of river channel cross-sections through time. This may be combined with repeated plane table maps of a river channel reach to provide information on planform change. However, much more detailed information on river bed topography is now needed for at least two reasons. First, there has been a growing recognition of the importance of spatially distributed form–process feedback in fluvial environments (e.g. Naden and Brayshaw, 1987; Naden, 1987; Richards, 1988). Although quantitative understanding of the nature of hydraulic and sediment transport processes is well developed, the linkage of these processes with river channel topography is still qualitative (e.g. Ashworth and Ferguson, 1986), with some exceptions (e.g. Dietrich, 1987; Dietrich and Whiting, 1989). Further, an over-emphasis on microscale topographic elements within river channels may have been to the detriment of quantitative modelling of river channel dynamics at the mesoscale, where overall channel topographic characteristics become more important. There remains much uncertainty as to exactly how important microscale topography is in the control of larger scale river dynamics, but such a comparative evaluation must come from a physically based, distributed modelling strategy which can include scales of topographic representation at least as large as the river bend. The required computational flow models

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are available (e.g. Bernard and Schneider, 1992; Malin and Younis, 1990) but their application to natural river channels requires detailed information on the river channel topography.

Secondly, the role of topography in the context of river channels has received greater attention recently through suggestions that monitoring changes in river channel form may be a means of monitoring the bedload transport rate (Davies, 1987). Popov (1962) first analysed the basic concept of inferring bed material transport rates from map estimates of erosion volumes. Neill (1971) endeavoured to link river channel erosion to bedload transport, a technique applied to long-term large-scale channel dynamics in the braided Waimakariri River by Carson and Griffiths (1989) and to multi-year comparisons of long reaches of large, low-sinuosity rivers by McLean and Wolcott (1987) and McLean (1990). Ferguson and Ashworth (1992) and Ferguson *et al.* (1992) describe its application to small-scale short-term proglacial stream dynamics and begin to make links between the volume of morphological change and other measures of the bedload transport rate.

Clearly, both of these developments require the use of techniques that explicitly recognize the three-dimensional nature of river channel morphology and its change through time. Conventional surveying techniques, based upon repeated levelling of a series of cross-sections and plane table mapping, result in a trade-off between the spatial resolution of collected data points and the temporal resolution of sampling. Time spent collecting data points at higher densities and over wider areas is at the expense of reduced frequency of return to approximately the same data points to measure how the landform is changing. This necessarily implies a commitment to return to the same cross-sections, such that research design is committed to the initial evaluation of the field site rather than being able to evolve as the landform does. Data analysis is time-consuming as levelling information is generally hand-booked. In gravel-bed proglacial streams it is unusual to report temporal resolutions greater than 24 h (cf. Ashworth and Ferguson (1986) and Powell and Ashworth (1990)). Further, levelling has tended to place an inherent over-emphasis on cross-sectional variation in channel morphology at the expense of downstream variation, points in the cross-stream being separated by 0·1 to 0·5 m and points in the downstream by 5 to 20 m (e.g. Ferguson *et al.*, 1992). Although the structure of a river channel bed naturally implies greater morphological variation in the cross-stream sense, thus justifying the higher spatial resolution in the cross-stream direction, downstream variations may be equally important, particularly if the width of active transport remains, on average, constant.

This paper describes the methodological background to the combination of analytical photogrammetry and tacheometry used to acquire three-dimensional coordinates of a dynamic river channel and to construct a series of digital terrain models (DTMs). Some of the preliminary results obtained from the application of these techniques to a dynamic section of proglacial stream are presented. This information is used to undertake a detailed assessment of the quality of the morphological information acquired, and this has implications for future attempts to monitor river channel form.

METHODOLOGY

Field site

The field site chosen for this study is a 50 m length of actively braiding proglacial stream approximately 300 m from the snout of the Haut Glacier d'Arolla, in the Pennine Alps, Valais, Switzerland. Previous observations (Lane, 1990) revealed that this section of river channel was relatively dynamic with a markedly diurnal discharge regime fluctuating between low flows of 1 $m^3 s^{-1}$ and peak flows of 7 $m^3 s^{-1}$. Fieldwork was undertaken between late June and the middle of August 1992. Data collection for the acquisition of digital terrain models involved three aspects: the acquisition of photographs of the stream at reasonably frequent intervals; necessary survey to allow three-dimensional coordinates to be acquired from the photographs; survey of those areas which were not visible on the photographs.

Principles of photogrammetry

There is a long history of the use of photography in geomorphology to provide both qualitative and quantitative information on the nature of landform change. However, it is only recently, with developments

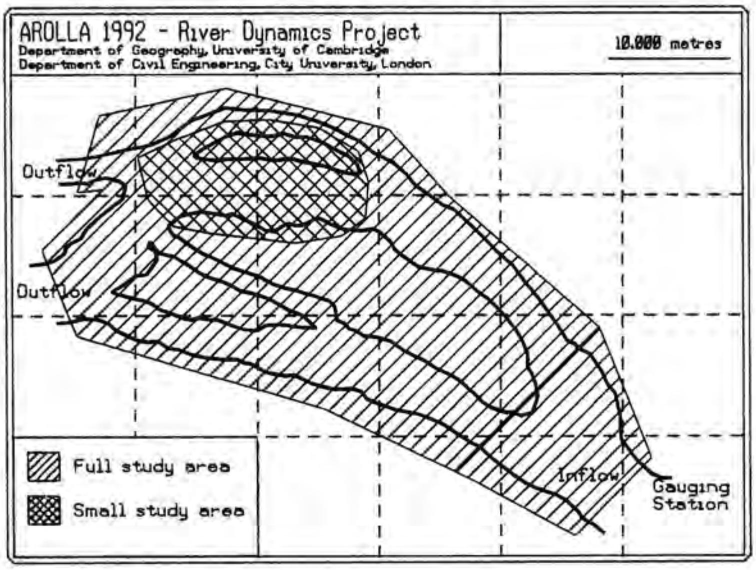
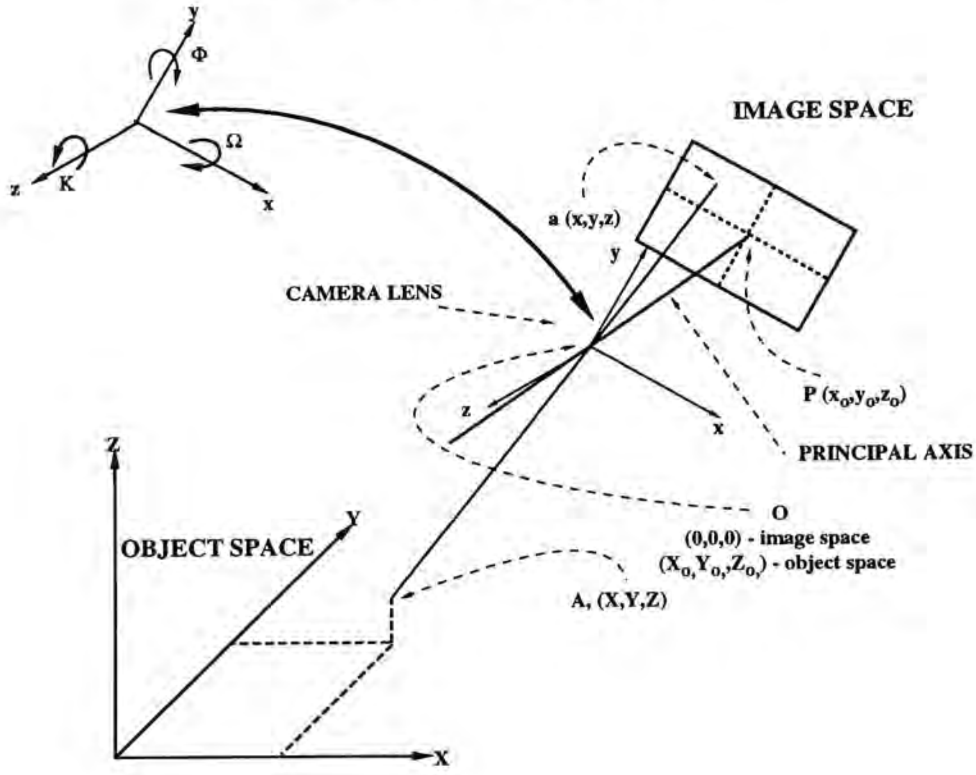


Figure 1. The field-site, showing both the full section of braided reach studied and the smaller area chosen for more intensive study

in photogrammetry, that the potential of the photograph to provide accurate and distributed three-dimensional information on a landform has been fully appreciated. The principles and advantages of using a photogrammetric technique in geomorphology are discussed in detail in Chandler and Moore (1989) and Lane *et al.* (1993) and only a brief summary is provided here.

It is generally assumed by photogrammetrists that the geometry of an ideal photograph is a special case of a perspective projection; a straight line passes between a point in the three-dimensional object space with associated object space coordinates, the perspective centre of the camera lens and a point in the two-dimensional image space with associated image space coordinates (Albertz and Kreiling, 1975; Slama, 1980). The basic projective transformation that describes the relationship between two such mutually associated coordinate systems (Ghosh, 1988) can be expanded into the collinearity equations (Figure 2). Important parameters represented in this equation are the position of the principal point of the camera in the object space (X_0, Y_0, Z_0), its orientation (Ω, Φ, κ) and the scale factor for each photograph. These parameters are important because, once known, they can be used to determine new object coordinates simply by measuring the image coordinates on two photographs. Analytical photogrammetry overcomes the stringent requirements of traditional analogue photogrammetry through the use of an interactive numerical solution, which greatly enhances the potential for the use of terrestrial oblique images (Kennie and McKay, 1987). The object space coordinates of a point are calculated from the collinearity equations by using measured image positions on two photographs obtained with known camera orientations and positions. However, the interactive nature of the equations means that by using measured image positions visible on each photograph of target points that also have known object space coordinates, it is possible to determine the position and orientations of the camera at the time the two photographs were obtained. This can be achieved using one of several different mathematical procedures, perhaps the most powerful of which is the bundle adjustment (Granshaw, 1980), where the positions and rotations are derived in one simultaneous least-squares estimation. It is not necessary to measure and maintain each camera position and orientation during field survey. A minimum of three coordinated points in the object space is necessary, but more points should be provided because redundancy increases the reliability of the estimation. These extra or redundant points are used in the least-squares estimation to improve the result and assess the precision of the estimated parameters (Chandler *et al.*, 1987; Chandler and Moore, 1989). This bundle adjustment is powerful because it can be extended to include the stochastic properties of both survey measurements associated with the coordinated points in the object space and the image measurements. Ultimately it allows the use of standard 35 mm photography (e.g. Chandler *et al.*, 1989).



The Collinearity Equations;

$$x = \frac{-c[m_{11}(X-X_o)+m_{21}(Y-Y_o)+m_{31}(Z-Z_o)]}{[m_{31}(X-X_o)+m_{32}(Y-Y_o)+m_{33}(Z-Z_o)]}$$

$$y = \frac{-c[m_{12}(X-X_o)+m_{22}(Y-Y_o)+m_{32}(Z-Z_o)]}{[m_{31}(X-X_o)+m_{32}(Y-Y_o)+m_{33}(Z-Z_o)]}$$

x, y, z	=	co-ordinates of point a in the image space
X,Y,Z	=	co-ordinates of point A in the object space
X_o,Y_o,Z_o	=	co-ordinates of perspective centre of the lens in the object space
k	=	scale factor
$m_{11}..m_{33}$	=	elements of the rotation matrix which are functions of Ω, Φ and K on
c	=	the focal length of the camera

Figure 2. The relationship between the object space and image space in the special case of an ideal perspective projection. The collinearity equations describe the relationship between two such mutually associated coordinate systems

The most important advantage of analytical photogrammetry is the increased flexibility which allows low-cost small-scale photogrammetric sorties using terrestrial, oblique images that can be acquired from any good vantage point. Three-dimension coordinates can be obtained for any point on the landform that is visible on both pictures. Analysis of the photographs takes place in retrospect, after all photographs have been acquired and the full landform evolution observed, such that data collection can be orientated to those areas which in retrospect prove to be most interesting. Data collection is non-contact, which may be important especially in the case of fragile stream banks (Collins and Moon, 1979), given the problems associated with the use of erosion pins (Lawler, 1989). The photogrammetric approach allows increased control over the temporal resolution of sampling. Photographs can be acquired relatively easily and cheaply; use of the analytical technique means that even photography acquired by 35 mm cameras may give acceptable results. Finally, the information obtained from the pictures in digital, generally a set of three-dimensional coordinates, and is therefore ideally suited to further manipulation using terrain modelling packages. These general points are discussed more fully in Lane *et al.* (1993).

Application of photogrammetry to monitoring dynamic river channels

The fieldwork requirements for the application of photogrammetry as a landform monitoring strategy are two-fold: survey and photography. A three-dimensional object space coordinate system was established using conventional survey (tacheometer), and points visible on the photographs (the photocontrol) were linked into this survey. Three control stations were used in this study, and observations made from each station to every other station (vertical and horizontal bearings and straight line distance) and every photo-control point (vertical and horizontal bearings). Natural features can be used for photocontrol points, but in this study a series of small targets was installed on exposed bars within the reach of interest. There was occasional target loss, and to combat this problem new targets were installed as required. Any remaining old targets were also resurveyed.

The fieldsite (Figure 3) was ideally suited to a photogrammetric sortie with a number of suitable vantage points. A large format photogrammetric camera (Wild P-32 model) was used to acquire the photographs. This is accurately calibrated, which simplifies the computational procedure, leads to more reliable results and the larger format allows extra detail to be obtained from the pictures as compared with non-metric cameras. Some consideration was given to the film emulsion used, as the grain size limits the spatial resolution of acquired information. In practice, the spatial resolution is coarser as the real limit on spatial resolution is the precision defined by the bundle adjustment, a product of both photogrammetric and survey measurements. Two camera positions were chosen, their optimal location being defined by two conflicting requirements. It is desirable to maximize the ratio of the camera separation distance to the distance of the cameras from the area of interest, as this maximizes the precision of the photogrammetric solution. However, if this ratio is too large, it becomes impossible to view the photographs as a stereo-pair and therefore digitize them. Hence the cameras were located such that this ratio was approximately 1 : 4 and therefore within the

Figure 3. The field study stream at 8 a.m. on 17 July

generally acceptable range of 1 : 3 to 1 : 12. The camera positions did not need to be fixed. Photographs were collected daily at 10 a.m. throughout the period of study. On days when the river channel was more dynamic, the time between epochs was decreased to a minimum of 2 h.

The process of extracting spatial data from the photographs was undertaken in the laboratory and made use of an *Intergraph* analytical plotter. The first stage of analysis involved defining a three-dimensional coordinate system based on the control survey and computing the coordinates of the photocontrol points within that system. This used a least-squares adjustment package with a three-dimensional variation of coordinates method to derive estimates for the best-fit positions of both control stations and photocontrol points from the given set of survey measurements. At this stage, observed photocontrol point movements between periods were checked and found to be within the standard error associated with the calculated position of each point for any one period. The image positions of each photocontrol point on each pair of photographs were measured and this information used in the bundle adjustment to determine the camera parameters (position and rotation) of each camera at the instant each photograph was acquired. It was then possible to digitize each stereo-pair; the combined effects of the scale of the photography and the precision of the bundle adjustment made it possible to digitize any clast coarser than 0·015 m in diameter in the centre-foreground. The time associated with such a digitization strategy and the large amounts of data that would result required the instigation of a criterion for point collection. This was to digitize all major breaks of slope and then to add extra information to provide a more even distribution of points.

Data acquisition from underwater zones

The key problem with the photogrammetric approach is that in streams with high suspended sediment loads it is impossible to see the stream bed. This problem is in part countered by the diurnal discharge regime associated with a proglacial stream, such that large areas of the stream bed become exposed at the discharge lows of the early morning. In the case of the Upper Arolla glacier, this is generally between 9 and 10 a.m., and an example of this effect is provided in Figures 3 and 4. However, this does not overcome two problems. First, there are some areas of the river channel which will always be under water. Secondly, river channel change within this environment can occur on the scale of hours and therefore reliance on information obtained at a daily low flow may provide an unrepresentative record of patterns of erosion and deposition.

Figure. 4. The field study stream at 6 p.m. on 17 July

These problems were solved by rapid tacheometric survey of non-visible areas (detailed bed survey). This made use of the control network established for the photogrammetric sortie and a digital tacheometer. Observations of horizontal angle, vertical angle and slope distance (radials) to a prism were collected by wading through the stream with a survey pole. The tacheometer was linked to a hand-held data module and allowed information to be recorded automatically. In the field, data points could be collected and stored at a maximum rate of 240 per hour. Exposed bars and river banks could be ignored as information on these areas would be acquired photogrammetrically. Similarly, there were no restrictions on the locations from which this information needed to be collected, as compared with cross-section based studies. Data collection could be stratified to allow concentration on the most dynamic areas and, within those, the key areas for accurate topographic representation such as breaks of slope. The stored data were analysed rapidly through computer programs written to calculate three-dimensional coordinates from survey observations.

Construction and comparison of digital terrain models

The first stage of DTM analysis must concentrate on reconstruction of the full landform surface on the basis of the acquired three-dimensional coordinates. Aspects of terrain modelling of natural topography are reviewed in Petrie and Kennie (1987) and Moore *et al.* (1991) and are only briefly discussed here. The Delaunay Triangulation is increasingly being accepted as the most appropriate technique for use in modelling natural topography (Petrie and Kennie, 1987). All measured data points are used and honoured directly since they form the vertices of a unique set of triangles that represent the surface (Saalfield, 1987). Thus, the method copes effectively with the random distribution of data points associated with this method of data acquisition. Some modification of the Delaunay method is required to cope with breaks of slope as the triangulation is based upon the planimetric location of points.

This study made use of a package developed for roadway modelling, *Intergraph InSites/InRoads*, which operates on an *Intergraph* workstation; a typical triangulation involving 5000 points only takes a few seconds to complete and allows the incorporation of breaklines. These triangulations allow both visualization and the extraction of a wide variety of information on and from the landform surface. This can include contour plots, 2·5 D rendered images, longitudinal and cross-sectional profiles, the distribution of major morphological features and bar surface sedimentology. Ultimately it allows development of a geographical information system (GIS) where other information, such as near-bed flow velocity, may be superimposed and stored by position on the landform surface.

An equally useful approach to a consideration of individual terrain models for a number of epochs is based upon the inter-comparison of terrain surfaces between epochs. This allows both the visualization and quantification of the spatial distribution of patterns of erosion and deposition. In this case, use was made of a surface inter-comparison algorithm available within the *InSites/InRoads* package. This calculates the *exact* volume between two surfaces, using the triangle geometry of both. Each triangle from one surface is projected onto the second surface, to form small prismoids. The total cut volume and the total fill volume are then obtained by calculating the volume of each prismoid formed by the triangle on the first surface and the intersection of the vertices with the second surface. The result is a volume of cut, a volume of fill and a net volume of change (cut volume minus fill volume). The volume is only calculated for those areas that are common in terms of planform position. It is also possible to control the area used for comparison through placing a boundary on 'fence' around the area of interest, which restricts the area of volume comparison to areas within the fence. This is critical if exactly the same area is to be compared between epochs.

PRELIMINARY RESULTS

The acquired data consist of a series of surface elevations at a number of planform locations. The data sets analysed thus far are illustrated in Table I. A number of points arise from this table. Firstly, the potential density of coordinates that can be acquired photogrammetrically is greater than that possible using detailed bed survey. Nevertheless, the density of within-channel points is greater than can be achieved using conventional levelling techniques. Secondly, it is important to appreciate that a trade-off between spatial and

Table I. Summary of the data acquired thus far using both photogrammetry and detailed bed survey

				Photogrammetry		Detailed bed survey	
Date	Time	Description	Area coverage (m^2)	Number of points	Density (pts/m^2)	Number of points	Density (pts/m^2)
28 June	10 a.m.–5 p.m.	Full area record	838*	2654	10·2	699	1·2
5 July	10 a.m.–5 p.m.	Full area record	1140	3860	6·1	1631	3·2
7 July	5 p.m.–6 p.m.	Small area record	276	864	5·1	179	1·7
8 July	10 a.m.–11 a.m.	Small area record	235	1595	11·9	195†	1·9
8 July	2 p.m.–3 p.m.	Small area record	344	940	6·9	319	1·5
8 July	5 p.m.–6 p.m.	Small area record	325	1501	11·1	282	1·5
13 July	10 a.m.–7 p.m.	Full area record	1068	7901	14·0	1379	2·7
16 July	10 a.m.–11 a.m.	Small area record‡	561	2798	11·0	797	2·6
17 July	10 a.m.–11 a.m.	Small area record	330	2399	11·2	185†	1·6
17 July	2 p.m.–3 p.m.	Small area record	331	948	7·4	215	1·1
17 July	5 p.m.–6 p.m.	Small area record	383	1131	10·9	288	1·0
18 July	10 a.m.–5 p.m.	Full area record	1321	8643	16·2	853	1·1
19 July	10 a.m.–1 p.m.	Small area record	372	3946	20·8	661	3·6
19 July	2 p.m.–3 p.m.	Small area record	424	5960	27·2	278	1·3
19 July	4 p.m.–5 p.m.	Small area record	443	3688	20·1	270	1·0

* Reach still partially snow-covered
† Note the lower number of detailed bed survey points on days when the morning flow was particularly low
‡ Note that the small area study section was extended slightly further downstream

temporal resolution still applies to the detailed bed survey. It is possible to increase the density of detailed bed survey but this will be at the expense of more time spent in data collection. This proves problematic if the landform is changing during data collection, as the topographic surface will then contain a time dependence manifest in a spatial sense. A number of alternatives can be used to overcome this problem. Firstly, it may be possible to reduce the spatial density of sampling, an option that is considered below. Secondly, a smaller area can be studied. The research design used here aimed to capture both the long-term evolution of a large section of the river channel and the short-term evolution of a smaller area. Full area information was collected on days when the river channel was relatively static. On days when the river channel was more dynamic, information was collected over a shorter time period and from a smaller area. This was the option chosen between 7 and 8 July, when the first warm periods of the summer significantly increased river discharge and, correspondingly, the rate of change within the reach (Table I). It would also be possible to increase the intensity of data collection by using more than one tacheometer.

An example contour plot generated from the triangulation is shown in Figure 5. The series of digital terrain models produced thus far allows easy visualization of the nature of river channel change during the study period. Some extraction of data from these terrain surfaces has been undertaken and Figure 6 shows a series of river bank profiles by way of an example; a more detailed analysis of bank retreat is currently under way, providing both an estimate of lateral input when calculating bedload budgets and information on the spatial relationship between different retreat rates in the downstream direction. The inter-comparison of terrain surfaces also provides interesting information. Figure 7 shows the differences that result from comparing the surface of 5 July to that of 7 July and that of 7 July to the morning of 8 July, based upon a triangle comparison of each pair of surfaces. As these diagrams show, this approach allows easy visualization of the spatial patterns of erosion and deposition. Between 5 July and the evening of 7 July, the section of river channel in the small study area began to shift towards the right bank. The result was trimming of the downstream end of a bar attached to the right bank, which had formed between 28 June and 5 July. Concurrently, a small amount of fill was recorded along the left of the river channel, partly in response to the shift towards the true right. This was a trend continued overnight between 7 July and the morning of 8 July. The river channel continued to shift towards the right bank, again trimming the right-bank bar. The lower overnight flow was also associated with the deposition of a new mid-channel bar. This bar formation is likely to be a

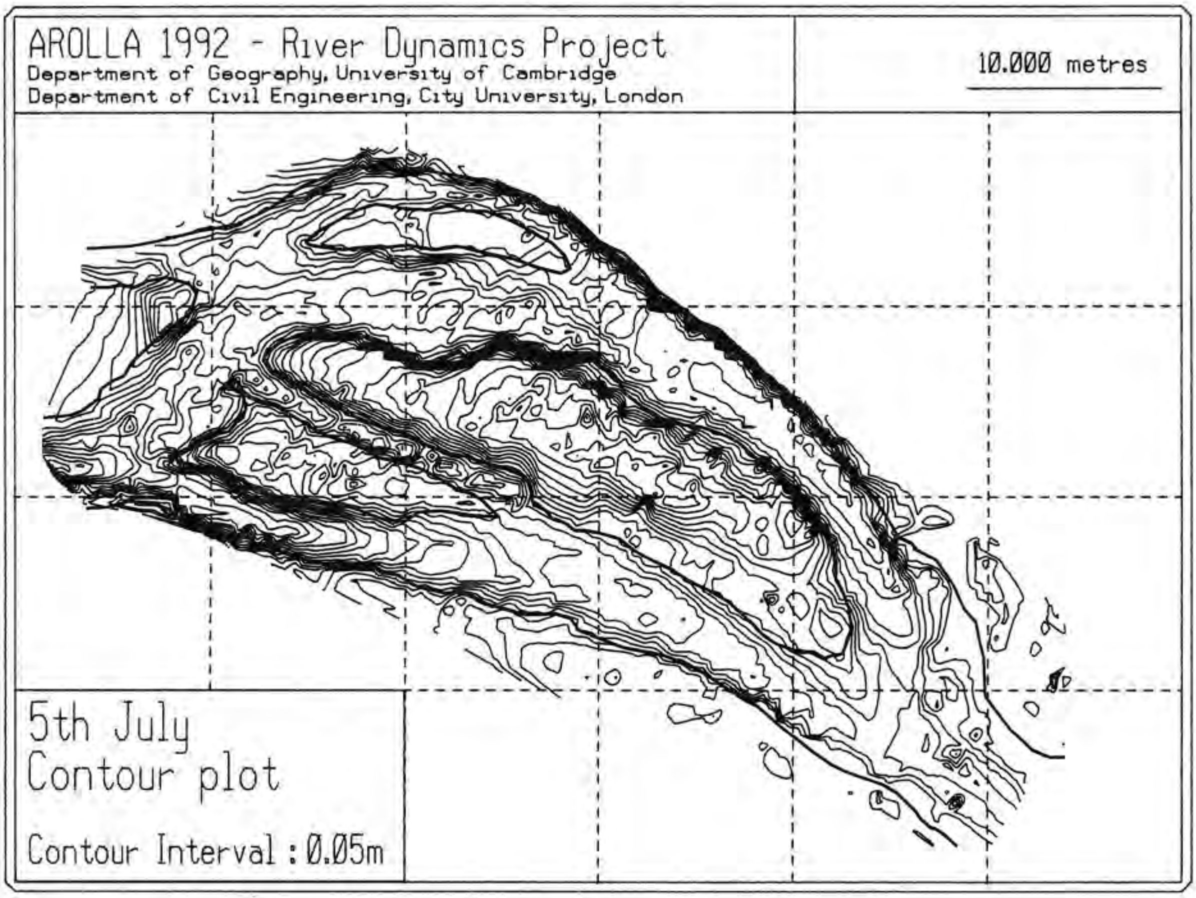


Figure 5. Contour plot of study reach using the 5 July dataset

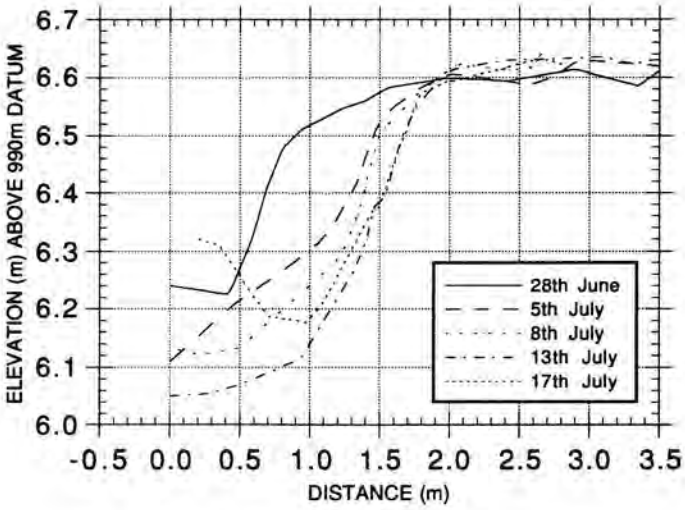


Figure 6. Bank profiles extracted from a sequence of DTMs

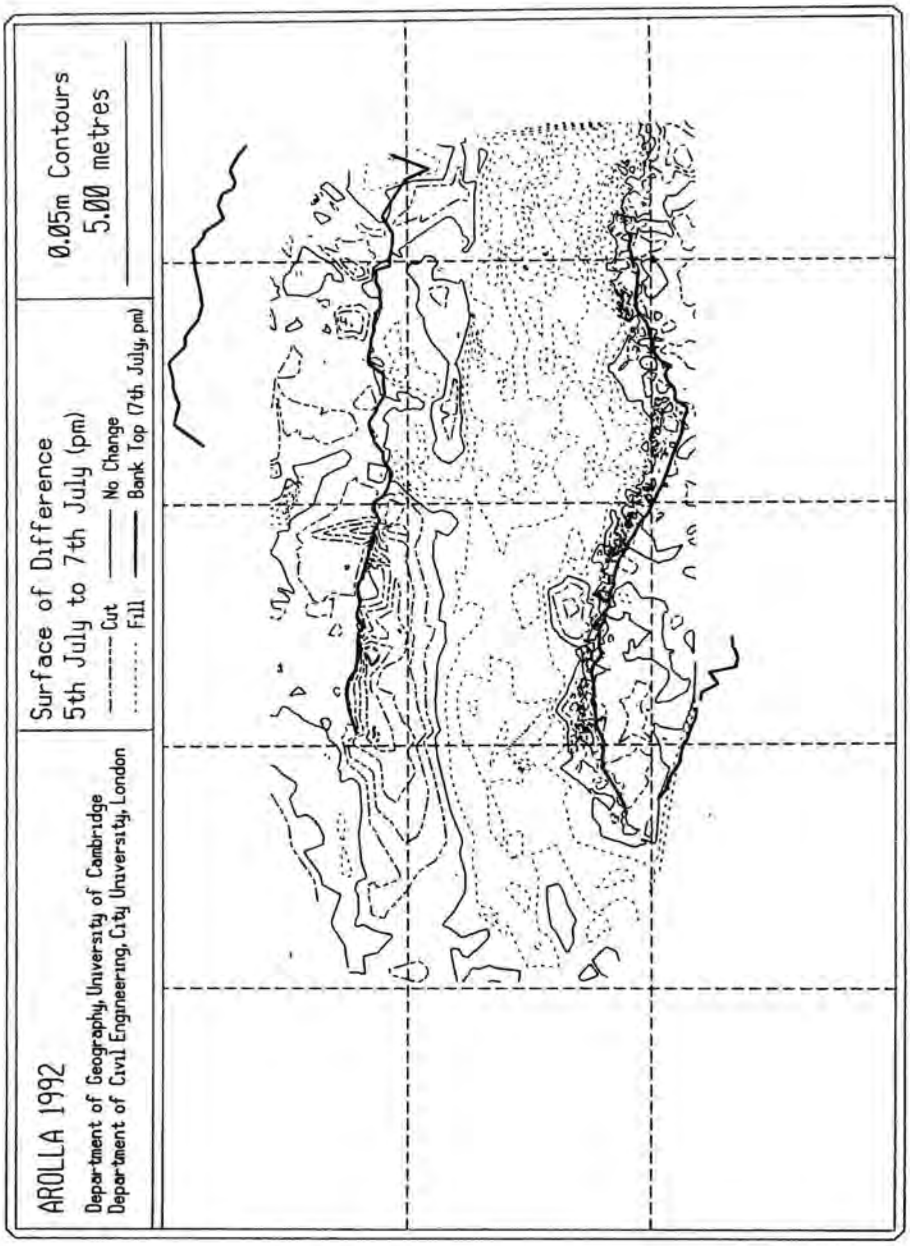


Figure 7. (a) DTM of difference obtained by subtracting the 5 July DTM from the 7 July (p.m.) DTM

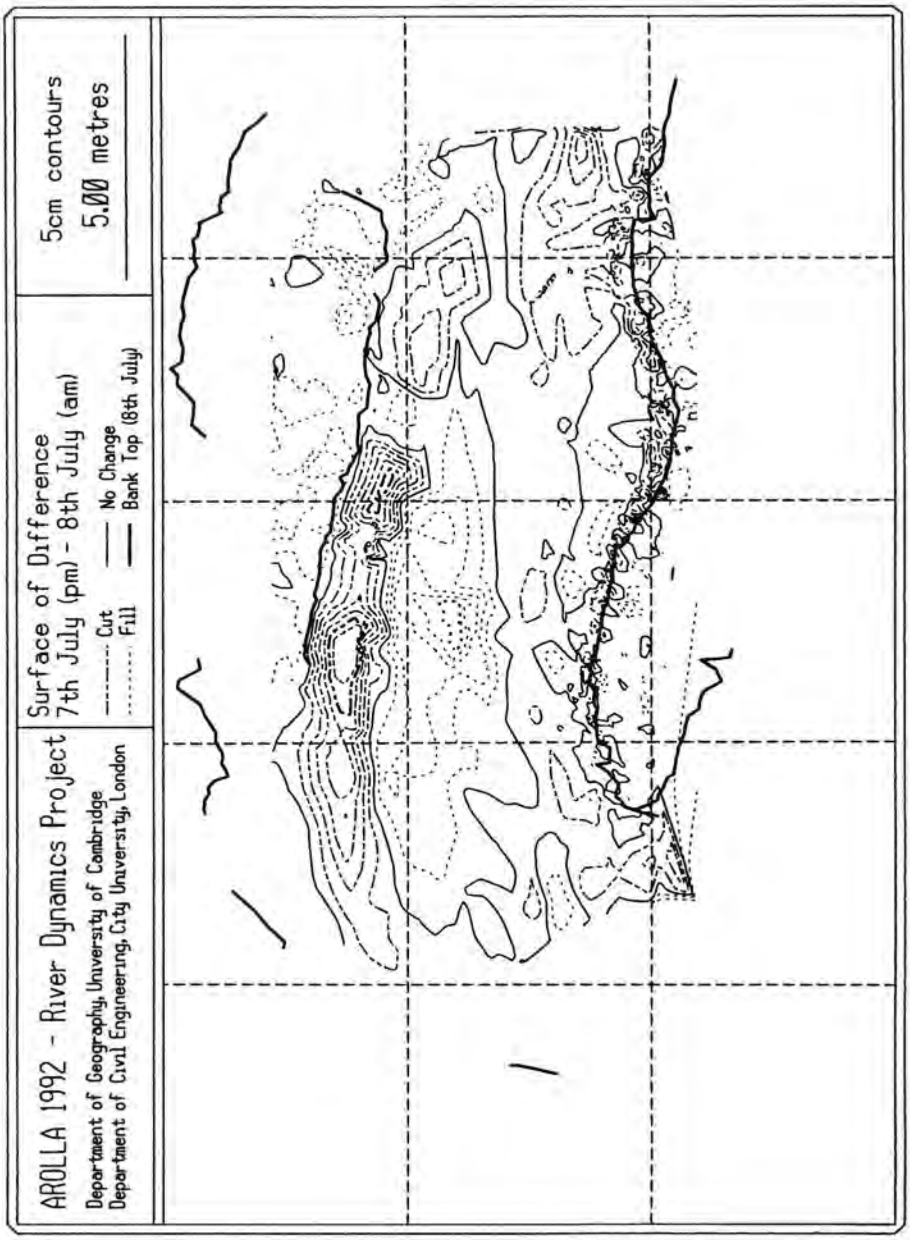


Figure 7. (b) DTM of difference obtained by subtracting the 7 July DTM from the 8 July (a.m.) DTM

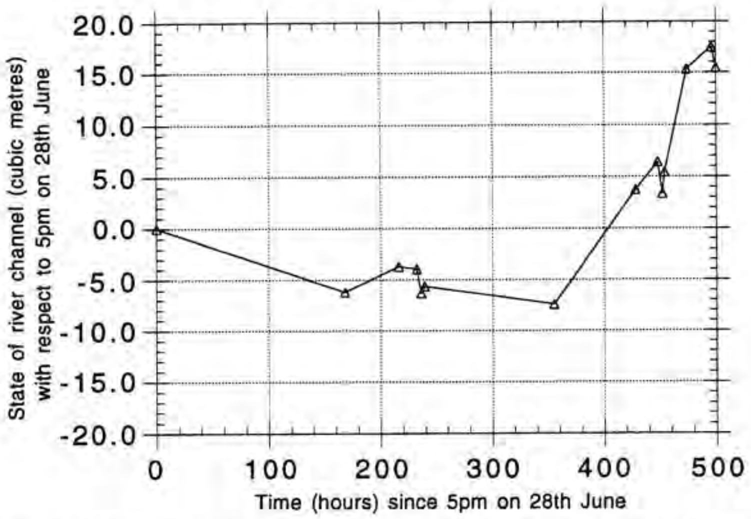


Figure 8. State of the small area of the river channel with respect to an arbitrary datum (28 June). Negative volumes indicate cut and positive volumes indicate fill. The difference between any two adjacent points represents the net change between those two points

product of the shift towards the right bank of the main river channel but would itself cause the river channel to shift further towards the right bank.

These comparisons can be extended beyond visualization to the calculation of the volumes of material eroded or deposited over a particular time-period. Figure 8 presents the 'state' of the small study area with reference to an arbitrary initial condition at the start of the period of study. The same area was compared on each occasion throughout the period through the use of the fence described above. The change in state between any two consecutive points is the net change in river volume. This figure suggests that there were two main phases in this period. The first was an increasingly negative state with progressive downcutting of the river channel until 13 July (350 h from 5 p.m. on 28 June). This was followed by a period of marked fill from 350 until 500 h.

DISCUSSION–AN ASSESSMENT OF THE QUALITY OF ACQUIRED TERRAIN INFORMATION

The preliminary results presented in the previous section indicate the potential of this approach to provide detailed information on river channel topography in a form that is of use for further morphological analysis. However, despite the advantages of combining a technique that allows rapid data collection with a terrain modelling approach, which recognizes the spatial variability in landform morphology, it is critical to consider the quality of the information that is being produced. This must be done with reference to four aspects: the quality of individual data points that represent the surface; the quality of each triangulation associated with each set of data points; the quality of the representation of the real topography and its change through time by the set of terrain models; and the quality of the inter-comparison of terrain models.

Quality of individual data points

In the context of individual data points collected for this study, quality may be downgraded by either random, gross or systematic errors. Random errors, which control the level of precision in coordinated data, represent variations of measured values under the same conditions (Cooper, 1974); for instance, if the same angle were measured more than once, the same result would not be obtained with every measurement. Gross errors, which control the reliability of coordinates, are blunders made by observers or errors introduced by malfunctioning equipment (Torlegard, 1980). These can be detected if there is some data redundancy, i.e. where more measurements than the minimum required to make a particular estimation are available. Systematic errors, which control the accuracy of individual coordinates, arise from the mis-specification of the functional model (for instance the use of the incorrect form of the collinearity equations

Table II. A summary of the major causes of error affecting individual data points in this study

Error type	Cause of error	Photogrammetry	Detailed bed survey
Random: determines precision	Measurements associated with the control network	Detectable because of repeat observation during the control survey	Detectable because of repeat observation during the control survey
	Measurements associated with the photocontrol network	Detectable because of repeat observation during the photocontrol survey	
	Measurements associated with radial observations		Undetectable as no repeat observation
	Measurements associated with data acquisition: controlled by sophistication of measuring instrument, image quality	Detectable if there is repeat digitization of the same point: this is difficult to undertake for every photogrammetrically acquired point but was undertaken for a subset	
Gross: determines reliability	Incorrect entry of manually recorded control network information	Detectable through design of a control network that provided data redundancy	Detectable through design of a control network that provided data redundancy
	Incorrect entry of manually recorded photocontrol network information	Detectable through design of a photocontrol network that provides data redundancy	
	Incorrect measurement of instrument or target heights		Undetectable
	Incorrect measurement of surveying pole height		Undetectable
	Incorrect entry or mis-interpretation of manually recorded radial observations		Undetectable but minimized through the use of automated recording
	Misidentification: digitization of what appears to be the same point on a pair of photographs but which isn't	Undetectable	
Systematic: determines accuracy	Deviation of the photographs from the ideal case of the perspective projection, causing the collinearity equations to become invalid	Minimized through use of a calibrated photogrammetric camera	
	Non-vertical surveying pole		Minimized through use of spirit level attached to surveying pole

in a photogrammetric analysis). Systematic errors are particularly difficult to detect (Chandler, 1989) but may be minimized through consideration of the appropriateness of the functional model adopted.

The relative importance of these errors is critically dependent upon the ability to detect them. Table II provides a classification of the sources of error and their detection. This shows that the quantity of undetectable error in the detailed bed survey is markedly greater than in the photogrammetry. For instance, the photogrammetric observations are more reliable because of the data redundancy associated with the collinearity equations (four equations and three unknowns). Thus although the assessment of individual coordinates is difficult, the quality of the photogrammetrically acquired coordinates is likely to be better than the

Table III. An assessment of the effects of incorporating breaklines on surface representation

Comparison	Cut	Fill	Net
13 July compared to 16 July: without breaklines	$5{\cdot}032\,m^3$	$10{\cdot}880\,m^3$	$-\ 5{\cdot}845\,m^3$
13 June compared to 16 July: with breaklines	$2{\cdot}093\,m^3$	$13{\cdot}266\,m^3$	$-11{\cdot}173\,m^3$
Difference	−58·4%	+18·0%	−91·1%

detailed bed survey. It should be emphasized that the photogrammetry is only more reliable because the field survey technique used in this situation is weak. Time constraints prevented repeat observation of the same point from any one location (thus reducing precision) and observation of the same point from a second location (thus reducing reliability).

Quality of the triangulation that represents a surface

This is essentially concerned with errors introduced as a result of fitting a triangulated surface to the dataset. Two problems were felt to need further consideration in this study. The density of photogrammetrically acquired points close to the water edge was often markedly greater than that of the adjacent detailed bed survey. As a result, the triangulation inherently gave more weight to each bed survey point, often connecting it to between 10 and 20 photogrammetrically acquired points. In practice it may mean that points are connected to each other in such a way as to distort the true nature of the bed topography. This problem was reduced by the incorporation into the surface of photogrammetrically acquired water edge information. This composed a series of line strings that marked the boundary between the detailed bed survey and photogrammetrically acquired river bank information. These were incorporated into the surface as breaklines across which the triangulation algorithm is not permitted to place triangles, thus limiting the number of photogrammetrically acquired points connected to each detailed bed survey point and reducing the error problem described above. Comparison of volumes of cut and fill between two triangulated surfaces with breaklines and without revealed that a failure to include such breaklines could have a substantial effect on calculated volumes (Table III). It should be noted that the breakline effect in this example is an extreme case as there was an area within the 13 July surface that had no detailed bed survey as a result of extreme flow conditions. Additional breaklines were used to allow detailed bed survey points upstream and downstream of this area to connect, so preventing the connection of photogrammetrically acquired data on both sides of the particular section of river channel.

The second problem concerns edge effects. These occur through triangulation along the boundaries of the area of data collection where a surface may be fitted between points when it should not exist. This problem can be reduced in two ways. Data can be collected from areas that lie outside the area of immediate interest. Thus the edge effects are removed to an area whose representation may be less critical. Secondly, once a surface is triangulated, it is possible to visualize the triangles and the data points used in generating the surface concurrently. Triangles that are likely to be associated with an edge effect can then be deleted interactively. Again the importance of this is illustrated by a volume comparison, this time for the full area epochs of 28 June and 5 July (Table IV). Removal of edge effects tends to reduce the amount of apparent volume change, although the resultant differences are not as great as those relating to the use of breaklines. The reduction in volume change is expected as the location of points constituting the edge would vary between epochs, leading to over-estimation of change where these edge effects are present. In practice, specification of a fence during volume calculation can also eliminate edge effects.

Table IV. An assessment of the impact of edge effects on surface representation

Comparison	Cut	Fill	Net
28 June compared to 5 July: with edge effects	$35{\cdot}780\,m^3$	$27{\cdot}853\,m^3$	$7{\cdot}929\,m^3$
28 June compared to 5 July: with edge effects removed	$30{\cdot}170\,m^3$	$26{\cdot}088\,m^3$	$4{\cdot}081\,m^3$
Difference	−15·7%	−6·3%	−48·5%

Quality of the overall topographic representation

The third issue that needs consideration is the nature of representation of the river channel which will be a product of both the spatial and temporal density of data acquisition. Recent research has suggested a continuum of within-channel roughness elements related to the scale of channel form under consideration. These may be loosely described as grain, microform and macroform roughness (Prestegaard, 1983; Clifford *et al.*, 1992). For perfect representation of river channel topography at the grain scale it is necessary to measure the position and dimensions of every clast on the river bed surface. This is clearly not feasible with current technology. It is likely, however, that the techniques presented in this study have a resolution somewhere between the microform and macroform; this would be closer to the microform in terms of photogrammetrically acquired data, where it is possible to map each individual grain, if not individual grain dimensions, and closer to the macroform in terms of the detailed bed survey, where time constraints in the field are more important. Indeed, wading rod location in the detailed bed survey is clearly random at the grain scale, although may be systematic at the macroform scale (e.g. location of points along breaks of slope). It is therefore necessary to assess the exact nature of the topographic representation with reference to both the photogrammetry and the detailed bed survey.

In terms of the photogrammetry, the sampling strategy involved digitization of the major breaks of slope, with the addition of extra information to provide a more even density of points. This results in a problem when considering surface comparison, as it is impossible to ensure that a clast measured in the first epoch would be remeasured in the second epoch, if it had not moved in the intervening period. Thus, for any one surface, there may be some discrepancy between epochs in terms of surface representation that is a product of data acquisition, rather than morphological change. This was assessed by the same collector digitizing the same area but on two separate occasions and by comparing the two terrain surfaces that result. Volume comparison of the two surfaces suggested a cut per unit area of $0{\cdot}0055\,m^3\,m^{-2}$ and a fill per unit area of $0{\cdot}0057\,m^3\,m^{-2}$. This was spatially variable and clearly dependent on whether or not a clast digitized in one epoch was detected in the second. If this is scaled up to the small area study, the error in volume calculations is approximately $0{\cdot}15\,m^3$, substantially less than the observed volumes of cut and fill between epochs (Figure 8).

Given the constraints on the spatial and temporal resolution of the detailed bed survey it is necessary to consider the scale of representation that the survey achieves. This is potentially useful as once the level of topographic information detected is defined it may be possible to assess rigorously the sampling design for future monitoring. On 5 July the detailed bed survey spacing was decreased in the field from 0·4 m to approximately 0·1 m over a small area for the purpose of assessing the density of points below which information will be lost. The area chosen was in the middle of the channel and therefore allowed comparison with the observed density of detailed bed survey obtained on other occasions. The *InSites/InRoads* thinning algorithm was applied to the surface to assess the amount of information lost as detailed bed survey points were progressively removed from the surface. This algorithm allows a number of criteria to be specified as to exactly which points are retained (such as a high/low pass which will only retain those points that are local maxima or minima), with the net effect that by combining criteria it is possible to obtain a set of surfaces, each with different point densities. Each thinned surface was triangulated and subtracted from the original surface which contained all the detailed bed survey points. Figure 9 shows the volume of information lost as the density of points is progressively reduced (in the computer) from that originally obtained in the field study. Although the thinning algorithm imposes some criteria for point retention and points for retention are not selected randomly, this will be countered to some extent by the sampling strategy adopted in the field, based upon collecting points that represent breaks of slope. Figure 9 suggests a rapid increase in error with point densities less than 3·5 per m^2, corresponding to an average point spacing of around 0·5 m. This may correspond to the boundary between the macroscale and microscale roughness elements. At spacings less than 0·5 m there is a small decrease in error, but this is minimal and further major reductions in error could not be expected until all the microscale elements are recorded, requiring a spacing of 0·01 to 0·05 m (or 4000 to 10 000 points per m^2) for the grain size in this stream. This needs qualification for two reasons. In the acquisition of detailed bed survey points, there was some systematic sampling (e.g. breaks of slope)

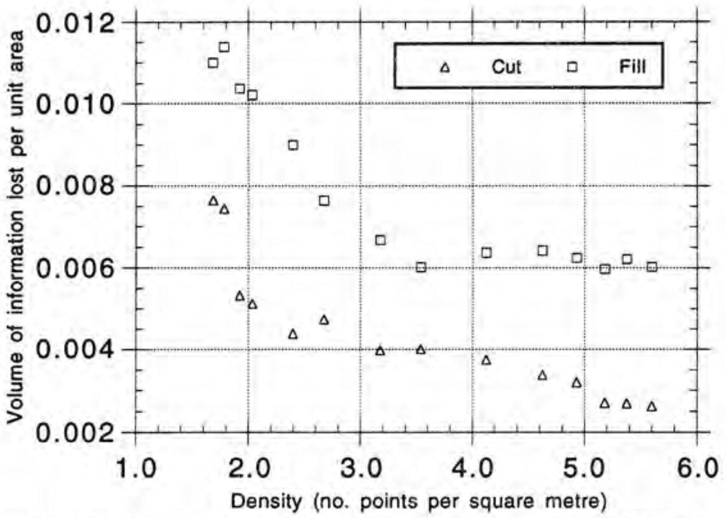


Figure 9. Plot of surface error (per unit area) against the density of detailed bed survey points

which the point thinning analysis does not allow for and which should make lower densities of points more acceptable. Secondly, if the maximum error volumes per unit area in Figure 9 are scaled up to the area of detailed bed survey, the error in any single volume calculation is of the order of $0{\cdot}3\,m^3$, substantially less than the observed amounts of net channel change (Figure 8), except for the proximate comparisons in the 200 to 250 h time-period.

This discussion can also be extended to temporal assessment of river channel change. It is only when the topographical information is obtained at closely spaced points in time that it is possible to detect the real nature of the river channel dynamics. Figure 10 shows the cumulative amounts of cut and fill on the basis of all data obtained thus far from the small area in this study. Also superimposed onto this figure are the cumulative amounts of cut and fill obtained by comparing surfaces on a much coarser temporal resolution, ignoring three terrain surfaces obtained between 5 and 8 July and four obtained between 16 and 19 July. The figure suggests that the cumulative amounts of cut and fill are progressively underestimated as the length of time between surface comparison is increased. Hence, although Figure 8 may be an adequate

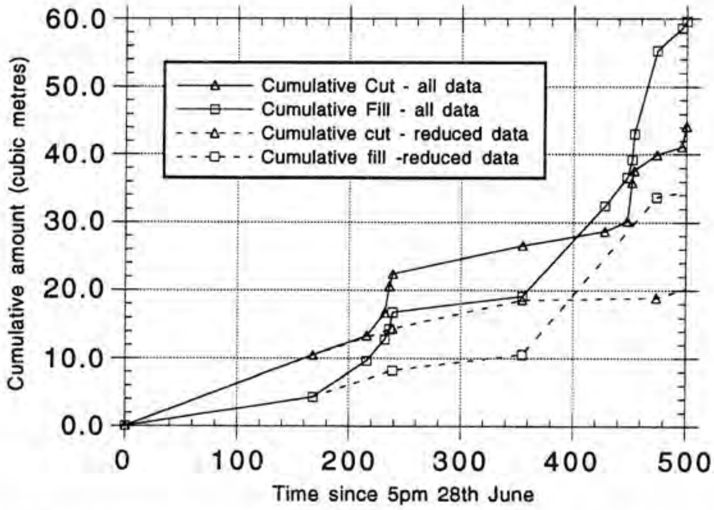


Figure 10. Plot of the cumulative amounts of cut and fill to illustrate the progressive under-estimation of the volume of material transported as the time between surface comparisons is increased

representation of the state of the channel at a particular point in time as compared to 5 p.m. on 28 June, the actual path of change between dates is not necessarily that shown. Indeed, it is probable that some idea of the actual change that the river channel was undergoing is only obtained for the intensive monitoring periods 5 to 8 July and 16 to 19 July. This implies that if morphological change is to be used to estimate the sediment transport rate over a period, then close attention must be given to whether or not there have been unmeasured erosion or deposition episodes within that period. This does not necessarily require continual monitoring of the river channel for closely spaced time periods, but design of a fieldwork strategy that allows flexible data collection in terms of both time (the frequency of re-survey) and space (stratification of sampling to zones of maximum activity).

Quality of information obtained from surface comparison

Surface comparison can involve any one of a number of techniques of varying sophistication: cross-section comparison, grid comparison and triangle comparison. The most rigorous means of surface comparison makes use of the triangle method described in the previous section. Because this represents the exact volume between two surfaces, any inaccuracies in the calculation are a product of the surface representation and not the calculation itself. However, this is an extremely sophisticated method of surface comparison and by necessity makes use of large amounts of computational time. Cross-section and grid comparisons are more rapid.

Current assessment of erosion and deposition in dynamic river channels is entirely based upon cross-section comparison (e.g. Ferguson *et al.*, 1992) using fixed cross-sections established in the field and repeatedly surveyed through time. It is possible to assess the effectiveness of a cross-section based approach by reference to volume calculations based on triangle volumes using the InSites/InRoads package. It makes use of the trapezoidal rule for volumes and is often labelled the mean end-area method where:

$$\text{Volume of cut} = \sum_{i=1}^{n} \frac{D_{n-1n}(A_{\text{cut}n-1} + A_{\text{cut}n})}{2}$$

$$\text{Volume of fill} = \sum_{i=1}^{n} \frac{D_{n-1n}(A_{\text{fill}n-1} + A_{\text{fill}n})}{2}$$

$$\text{Net} = \text{Volume of cut} - \text{Volume of fill}$$

where A = cross-section area and D = cross-section separation.

Errors could be introduced into these calculations through one of two sources. Firstly there could be error due to the calculation itself, and in particular the estimation of the cross-section area. Secondly, error will be introduced through the effects of intervening cut and fill between cross-sections; the assumption of a linear variation in cut or fill between 'end-areas' may be invalid. The importance of this error will be dependent upon the cross-section spacing, as with greater cross-section spacing the possibility of variation in the spatial pattern of cut and fill between two cross-sections increases. The total magnitude of error will also increase with the width of cross-section and length of reach under comparison.

To assess the quality of this calculation, cross-sections were located in parallel along a defined alignment within the river channel. Again, volumes were only calculated where in planform terms the two surfaces were common and additional controls were made over the area compared by use of a rectangular fence. The width of the rectangle was chosen to correspond to the specified cross-section width. The reach length was divided by the number of cross-sections being used in the calculation, minus one, to define the cross-section spacing and estimates of cut and fill calculated. This was repeated for a number of cross-section spacings. To consider the quality of these calculations, they were compared with the exact amounts of cut and fill as revealed by the triangle volume calculation. The comparison has the advantage of cancelling out the width and length effects such that no further standardization is necessary and the amount of information retained can be directly related to cross-section spacing. The analysis was undertaken for two separate periods to assess the consistency of the results. Figure 11 shows the percentage of information obtained for each cross-section spacing (the volume of cut, fill or net change as a percentage of the volume of cut, fill or net

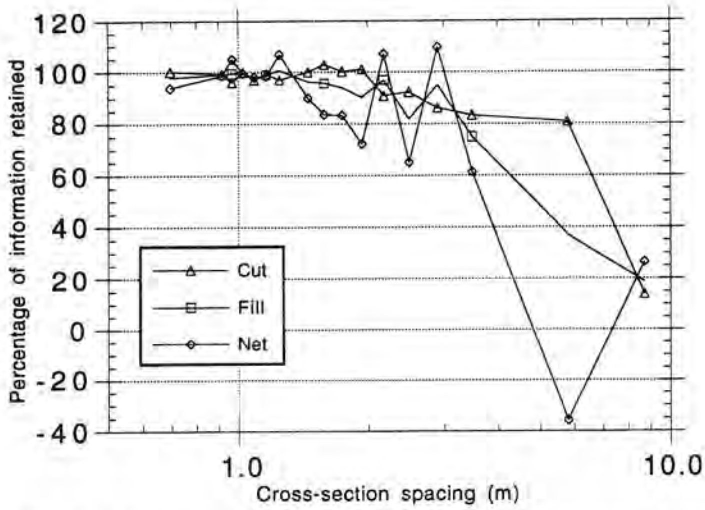


Figure 11. Plot of the percentage of information retained against cross-section spacing

change revealed by the triangle comparison). This suggests that a cross-section spacing of less than 2 m is required for an estimate of cut or fill to be within 20 per cent of the correct value. This can be compared with previous attempts to use cross-section based approaches to quantify spatial patterns of erosion and deposition in braided streams of similar size. These have used cross-section spacings as great as 5 m (Ferguson *et al.*, 1992) in streams of comparable width. Such a comparison, however, is not entirely valid as the probability of intervening cut and fill between 'end-areas' will vary between environments. Similarly, effective design of a sampling strategy (e.g. Ferguson *et al.*, 1992) may reduce this problem, but this is only feasible if the approach is terrain-based (as opposed to cross-section based) and there is no restriction on location.

Thus far, emphasis has been placed upon the exactness of the triangle-based volume calculation. However, with surfaces that contain a large number of triangles, this calculation is demanding of computer time and memory, generating a surface that may contain upwards of 50 000 triangles. A second alternative is grid comparison, which is more rapid and generates less information. It is a surface-based means of comparing terrain surfaces but rather than making use of the Delaunay triangulation it involves the draping of a grid at

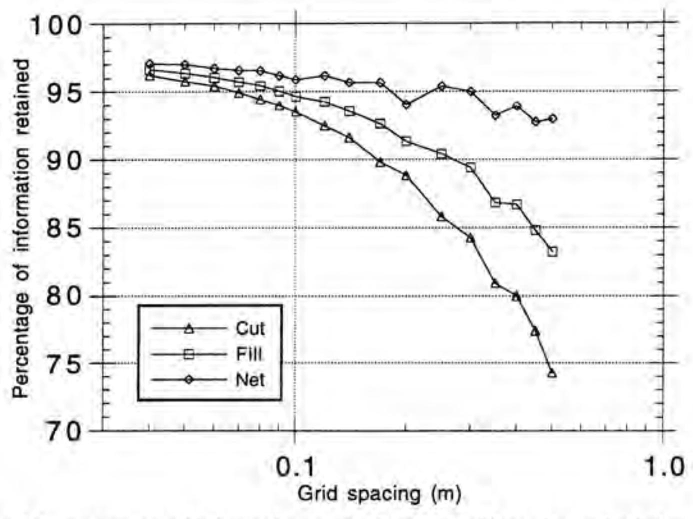


Figure 12. Plot of the percentage of information retained against grid spacing and relative computational time

a user-defined spacing, over each terrain surface. Each grid intersection defines the horizontal position of a grid vertex. The height difference is obtained by simply subtracting the two elevations at the same vertex on each surface. With subsequent triangulation this gives a surface of height difference. The amount of information lost can be minimized by making the grid spacing extremely small, but this is at the expense of computational time, which is inversely proportional to the square of grid spacing. Figure 12 shows the effect of grid spacing. This implies significant information loss with grid spacings greater than 0·1 m (100 points per m^2). At grid spacings much less than this, there is little improvement in information retention given the associated increase in computational processing time.

CONCLUSION

This discussion serves to illustrate the benefits that arise from the combination of terrestrial photogrammetry and rapid field data collection system with a terrain modelling approach. The use of the instantaneous record provided by the photograph allows the rapid acquisition of accurate data on river bed topography, particularly at low flows. When combined with tacheometric survey of the stream bed, this allows the construction of dense and accurate digital terrain models at a temporal resolution that can begin to match the rate of river channel change. The acquired information has been subject to a detailed assessment of quality. This suggests that the conventional cross-sectional approaches to river channel monitoring may need reappraisal, as they result in major inaccuracies in the estimation of morphological change at the cross-section spacings typically used. The methodology applied to this study is able to detect morphological components associated with the microscale in terms of the photogrammetry and the macroscale in terms of the tacheometry.

The information supplied from terrain models, which at least in the field are acquired rapidly, has a wide range of geomorphological applications. For instance, the DTMs illustrated in this paper are being used as a boundary condition for a two-dimensional river flow model, in which an upstream river discharge and three-dimensional bed topography are used to predict the spatial patterns of velocity. This method has the potential to reconcile deterministic process-based modelling approaches, with intensive field studies of within-channel processes through providing perhaps the key boundary condition.

There still remains the problem that the within-channel density of topographic measurement is poor at high flows when the bed is submerged. Future developments could involve increasing the density of detailed bed survey through the simultaneous use of more than one tacheometer. Alternatively, future research will apply this form of analysis to a clearwater stream where, with some correction for refraction, it should be possible to acquire information on subaqueous points on the stream bed from the photography.

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