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Developments in photogrammetry; the geomorphological potential

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Abstract: Current emphasis in geomorphology recognizes the need for the accurate representation of topographic form, reflected in the growth of digital terrain and elevation modelling. A key requirement of such strategies is the efficient acquisition of information in an appropriate form and at an appropriate resolution to the landform under consideration. The traditional use of photographs in geomorphology has been for interpretation, but developments in photogrammetry may allow the full advantages of the photograph as a means of acquiring and storing quantitative information to be used. The photograph can provide information on all areas visible on a photograph; the information is acquired retrodictively; the photograph preserves the spatial relationship of morphological units; the collection of photographs requires minimal landform contact; the photograph records extra explanatory information; and photographs can be obtained at an appropriate temporal resolution to the landform under investigation. However, optical and mechanical limitations imposed by traditional photogrammetric approaches have prevented its rigorous and widespread application to geomorphology. Developments within photogrammetry, notably the analytical approach, now open up wider geomorphological possibilities. The analytical approach overcomes these limitations through the use of an interactive mathematical model at the stage of photographic analysis. The obtained information is in a form directly suited to the construction of digital terrain or elevation models. This technique can be used both for landform monitoring and for the analysis of archival photographs to reconstruct historical landform change.

Key words: landforms, digital terrain models, surveying, photogrammetry, geomorphology.

I Introduction

Current emphasis in certain areas of geomorphology recognizes the need for the accurate three-dimensional representation of topographic form. This is illustrated in particular in modelling strategies used to understand landform evolution that are based upon spatially distributed form-process feedback (cf. Richards, 1987; Moore *et al.*, 1991) and is reflected in the growth of digital terrain modelling and Geographical Information Systems (GISs)

witnessed in many Geography Departments, at least in the UK. Such approaches require the accurate representation of three dimensional landform, both as a boundary condition for model input, and to verify model output. However, monitoring change in form may also provide a useful measure of process rate. In terms of contemporary monitoring there are processes that are elusive in current geological time, such as the bed material transfer process (cf. Gomez *et al.*, 1989; Carson and Griffiths, 1989). If a landform monitoring strategy can be designed that allows effective and quantitative monitoring of change in bedform, this would provide an estimate of process rate. Similarly, in past geological time, many high magnitude infrequent events such as landslides can only be monitored through consideration of change in form and this becomes possible if appropriate archival material on past three-dimensional form is available (cf. Chandler, 1989).

Central to the accurate representation of three-dimensional form is the Digital Terrain Model (DTM) or the Digital Elevation Model (DEM). Both represent a co-ordinate system, the DTM based upon a conventional Cartesian system that uses x, y and z co-ordinates and the DEM based upon a modified co-ordinate system that uses latitude, longitude and elevation (Doyle, 1978). Both have two key requirements for data input. First, there is a need for distributed elevation information that provides information on the whole topography, rather than on arbitrarily located points, at a spatial resolution that conforms with the structure of the model under development. Secondly, the temporal resolution of data acquisition must match the temporal scale of landform change under consideration. Conventional surveying techniques are limited in both respects. In dynamic environments it is possible to envisage 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. Developments within photogrammetry may provide the geomorphologist with a tool that helps reduce this problem, allowing the acquisition of dense and accurate information on the spatial extent of both contemporary and historic landforms if archival information is available. This information can be in a form suited to the construction of digitized terrain models and at temporal resolution that, at least in the case of landform monitoring, is controlled by the nature of the phenomenon under investigation rather than by the limitations of the techniques in use. This article will illustrate the advantages of the photograph as a means of providing and storing information on three dimensional landform, showing how developments within photogrammetry can increasingly allow the use of the photograph as a means of providing morphological information in a form directly suited to the construction of digitized terrain models.

II The photogrammetric advantage

Traditionally, aerial photographs have been used in geomorphology for air photo interpretation (API) to provide qualitative information on the nature of landform change. El Ashrey and Wanless (1967) used air photographs to monitor changes in form and the nature of the longshore drift process in a coastal environment. From sequential aerial photography it was possible to observe and measure changes resulting from sediment shift during the interval between dates of photography. Similarly, Lewin and Weir (1977) and Werrity and Ferguson (1980) used aerial photographs to define levels of river channel stability. Such studies simply exploit the two-dimensional information on object position that is retained within a single photograph. Using two photographs has the added advantage of the vertical height exaggeration provided by stereo-viewing and has been used in a number of geomorphological situations. Burton (1970) used API of stereo-models of the Calabrian peninsula, Italy, to identify incipient and potential landslides and slopes which were unstable due to soil creep. The small slope changes indicating instability were recognized more easily on the stereo-model than they were by walking over the ground. Similarly, Norman (1969) notes that the stereo-model is central to outlining the characteristic form of old landslips, even when their significance is almost lost on the ground. For instance, Matthews and Clayton (1986) used a series of 40 oblique photographs to establish the sequence of landsliding over a 50-year period at Stag Hill, Guildford, Surrey. Lewin and Manton (1975) note that, in the case of shore platforms, the stereo-view given by aerial photographs is central to the measurement of breaks of slope and minor slope segments which the ground surveyor, working in steeply dipping and differentially eroded coastal areas is unable to identify. In part of a study relating wind blowouts to vegetation change Lyon *et al.* (1986) used vertical scale exaggeration to distinguish between two cotton cover classes.

Photogrammetry is defined by Slama (1980) as '. . . the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring and interpreting photographic images and patterns of electro-magnetic radiant energy and other phenomena . . .'. The introduction noted the importance of the accurate quantification of form through the digitized terrain model. Lawler (1989a) notes that existing methods of landform monitoring fail to define fully the spatiotemporal variability in landform erosion and sedimentation rates and that there is a persistent degree of uncertainty in the field determination of landform change which can often frustrate attempts to test rigorously any newly emergent geomorphological theory (Lawler, 1989b). This is clearly a sampling problem in which the population is unknown but can be represented by sampling at a sepcific level of spatiotemporal resolution. However, Chandler (1989) points out that the terrain modelling approach assumes the efficient acquisition of sufficient data across space and through time to represent accurately the landform in question and it may be the case that existing models of landform monitoring may not meet this demand.

Photogrammetry may therefore take photographic interpretation one stage further by providing quantitative information on the landform under investigation, and in doing so meet the requirements of a digitized terrain modelling strategy. Further, it allows exploitation of several advantages of photographs as both a provider and a store of three dimensional information. In summary, the photograph can provide information on all areas visible on a photograph, the information is acquired retrodictively (the required information is collected from the photograph after the areas of major morphological change have been identified), the photograph retains the spatial relationship of morphological units, the collection of photographs requires minimal landform contact, the photograph records extra explanatory information and photographs can be obtained at a temporal resolution defined, rather than constrained, by the nature of the morphological change under investigation.

The geomorphologist is interested in the spatial distribution and morphology of landforms (Welch and Howarth, 1968) and the photograph records all points on a landform surface within the area covered by the image (Chandler and Moore, 1989) to a resolution that in theory is limited only by the grain size of the film in use. This is a particularly useful aspect in some instances. As Fraser (1983) noted in a study of the slope

stability of Turtle Mountain, in South Alberta, Canada, TM-71 crack motion detectors can be used to monitor accurately (*c.* 1 mm) the dilation and shear effects of a single gaping crack, but this represents only a small proportion of the total 5 million m^3 of rock wedge that could be susceptible to movement. Such a measuring scheme effectively examines the hypothesis that this crack and no other is the boundary of the unstable zone. The photogrammetric approach provides no limitations on the number of object points that can be measured (Lewin and Manton, 1975). A crack monitor provides a single measure of movement, but comparison of stereo-photographs from two separate epochs can theoretically provide an infinite number of measurements of movement, provided each point is measured on both sets of stereo-pairs. In terms of accuracy, Wickens and Barton (1971) used a photogrammetric technique to monitor small (2–3 mm) prefailure displacements on a rock slope to an accuracy of ± 0.15 mm.

The ability to acquire information at an improved spatial resolution is also illustrated in the calculation of glacier mass-balance and velocity characteristics. Brecher (1986) notes that, particularly in the study of large polar valley glaciers, ground survey methods can only provide a few measures of glacier surface velocity. Photogrammetry allows the determination of the rate of surface movement at a much larger number of locations, only limited, as in the case of landslides, by the number of points identifiable on each set of stereo-pairs. The same is true of other geomorphological problems. Kidson *et al.* (1989) note that precise conventional surveys of major dune systems are rarely attempted due to the complex topography and rapidly changing morphology, even though it is this very complexity and dynamism, resulting from the operation of aeolian processes over short time periods, that is of greatest interest to coastal scientists. Collins and Moon (1979) note that the complex and irregular topography of streambanks means that an extremely large number of individual readings are required to represent accurately the three-dimensional topography. Further there is often substantial spatial variation in bank erosion (and accretion) rates (e.g., Hadley, 1977; Hooke, 1979). As Lawler (1989b) notes, because photogrammetry is area- as opposed to location-specific, it does not gather information on topographic change from just a few points or sections. Rather, information can be obtained from a whole area of bank face, providing accurate information on the spatial variation in rates of landform change. this is particularly important when the study of landform characteristics demands a large sample size for a statistically viable sample to be measured.

Secondly, and related to the previous point, is the retrodictive nature of the photogrammetric analysis (Chandler and Moore, 1989; Lawler 1989b). Information is obtained from the landform during photographic analysis and after all photographs have been acquired and the full landform evolution observed. Conventional survey techniques clearly commit the geomorphologist to a predesigned survey sampling strategy based on subjective interpretation of the likely course of landform development (Matthews and Clayton, 1986). However, in the case of an effectively designed photogrammetric survey, there is no limitation on the amount of information that can be retrieved on surface form – because all information is stored it is possible to concentrate on those areas of the landform which in retrospect prove to be most interesting. As Brandow and Karara (1976) describe, the photograph furnishes a complete and permanent record that can be retrieved and reanalysed at any time. Further, because the photograph retains the spatial relationship between morphological attributes, it may be of use in the context of the recognition of spatially distributed form process feedback. It may be central to the identification of floodplain inundation zones where the spatial distribution of both natural and man-made features, as well as the topography itself, determines the probability that a particular floodplain zone will be inundated by a flood of a given magnitude (Lewin and Manton, 1975). Kalaugher *et al.* (1987), in a hazard assessment of cliff stability, illustrate how high level oblique photography allowed changes in process regime to be monitored and also how changing process regime on the beach led to evenutal oversteepening and failure of the cliff. The combination of retrodictive analysis and the preservation of the spatial relationship between morphological attributes provides the means to review data in the light of theoretical development. If a new theory requires morphological data of a different form from that originally collected, data recollection is possible.

The noncontact nature of the photogrammetric approach can also be advantageous (Welch and Howarth, 1968; Kennie and McKay, 1987). Brandow and Karara (1976) and Atkinson and Stethridge (1980) note that in the monitoring of coalmine roof stability there is a problem of acquiring substantial information from hazardous locations using standard field techniques. Similarly, Fraser (1983) and Franklin (1984) note that in the case of landslide monitoring, reinitiation of ground movement may preclude conventional monitoring techniques due to problems of access. The problem of hazardous access to landforms can in part be overcome if the monitoring can be undertaken from a platform which is not in direct contact with part or all of the landform itself. Thus, Small *et al.* (1984) show how the use of photogrammetry avoids the need for direct access to hazardous moraine embankments in a glacial environment. Brecher (1986) describes the advantage of the photogrammetric approach for highly crevassed glaciers on which movement is otherwise difficult. This point is also important when the effects of landform contact are considered. Collins and Moon (1979) note the fragility of streambanks and the fact that many could not be approached closely without danger of causing erosion falls or slumping. Erosion pins suffer from a number of problems; they are often cumbersome to implement (Welch and Jordan, 1983) and may lead to direct loosening of the surrounding material during insertion, resetting or measurement; they may lead to disruption of local stress fields; they may influence hydrometeorological processes (such as by creating preferential seepage zones); and they may reinforce the bank against mass-failure events (Lawler, 1989a). Similarly, in the case of sand dunes, excessive trampling will lead to disruption of site morphology (Kay, 1988). The photogrammetric approach will avoid the need for excessive landform contact and disturbance.

Fourthly, the photograph records a substantial amount of extra explanatory information. Lawler (1989b) notes how, in the case of bank erosion, zones of erosion and zones of accretion can both be identified whereas techniques such as erosion pin monitoring can only measure erosion. Similarly, it may be possible to obtain extra explanatory information on such factors as seasonal vegetation change, and the growth and disappearance of dessication cracks. Thus Norman (1969) used aerial photographs to identify a tonal/colour range within boulder clay zones, reflecting variations in moisture characteristics invisible to the human eye at ground level. Such information was central to the identification of areas liable to landsliding. Stafford and Langfelder (1971) also used tonal differences on aerial photographs caused by moisture content differences of sand, to map the highwater mark on beaches. Lyon *et al.* (1986) were initially interested in obtaining information on blowouts from aerial photographs. However such photographs also included information on vegetation type and cover, which became central to the explanation of the spatial distribution of such events. In a study of the dune systems at Braunton Burrows, Devon, Kidson *et al.* (1989) used false colour diapositives for the photographic mapping and found that this permitted greater ecological discrimination. Kirby (1991) used a photo-

grammetric technique to measure the microrelief of desert terrain to a precision of 1 mm, using vertical photographs taken with metric cameras on a lightweight gantry. It was possible to map individual clast dimensions (Figure 1), and clearly if such information is stored at an appropriate resolution on photographic material obtained for other purposes (e.g., for the monitoring of micromorphological change), it could be of great use. A key problem in fluvial geomorphology is the need for detailed spatial information on sedimentological distributions as input to spatially distributed models of form-process relationships. Obtaining such information conventionally leads to disturbance of the landform surface. Photogrammetry may permit the acquisition of such information, at least for subaerial zones, without such disturbance and at a much finer spatial resolution than bulk removal allows.

Indeed, there are instances where the photogrammetric approach may be the only means of reconstructing landform attributes. Moore (1974) describes the problem of

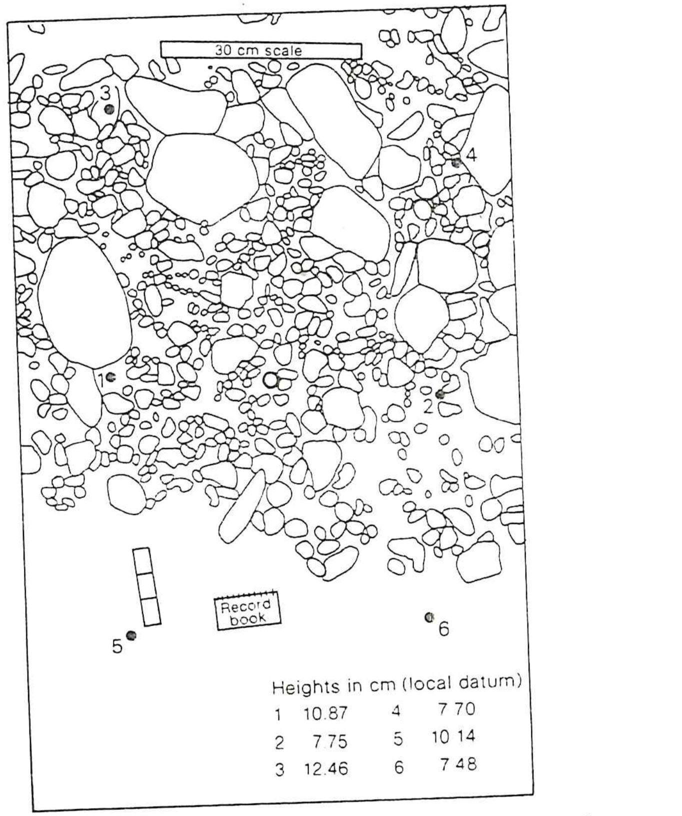

Figure 1 The microrelief of desert terrain acquired photogrammetrically.
Source: Kirby (1991).

inferring the general continuity, dip and strike of planes of discontinuity in boulder clays. However, in a study of the Lower Oxford Clay in Whittlesey, Cambridgeshire, it was possible to reconstruct the plane orientation by comparing photographs from successive epochs. In turn, such information became central to the design of a quantitative model that identified zones of instability and which was used to define a technique of clay extraction that minimized landsliding effects.

Finally, the photogrammetric approach also allows increased control over the temporal resolution of sampling. Effective design of a landform monitoring strategy requires the monitoring of landform change at a temporal scale appropriate to the rate of landform change (Lawler, 1989b). Although this implies that some knowledge of the rate of landform change is needed before a sampling strategy can be formulated, there are clearly some environments where conventional survey techniques are inherently limited. In the monitoring of rapid changes in channel planform dimensions in glacial meltwater streams there is a temporal limitation to the application of conventional surveying techniques. The surveying of a series of six cross-sections of a braided stream in Switzerland took on average four hours while upstream growth of a channel bar was observed at 0.5 m per hour (Lane, 1990). Although the photogrammetric advantage may be limited to subaerial channel changes, the combination of photogrammetric monitoring with conventional survey, means that the latter will need only to be undertaken for subaqueous zones. Application of such a technique in the same section of stream in the summer of 1991 allowed the number of subaerial cross-sections to be increased to 16 and the sampling frequency to be reduced to two hours. The saving in time taken in monitoring landform change enabled more detailed measurements of process to be undertaken. Photogrammetric analysis is subsequently being undertaken using photogrammetric epochs chosen with a temporal sampling interval that matches the landform change witnessed in a particular period. The same applies in other environments. Kidson and Manton (1973) illustrate how a properly constituted photogrammetric sortie can record a coastal situation in a matter of a few minutes which may be essential if all this information has to be collected within a single low-water tide because of a rapidly changing environment. Erlandson and Veress (1975) noted that using traditional triangulation to monitor structural deformation provided a best temporal resolution of two weeks, while using a photogrammetric method it was possible to increase the resolution to 24 hours. Brandow and Karara (1976) conclude that the photogrammetric approach means less time must be spent mapping geological features while more time can be spent measuring and evaluating process. Indeed the temporal resolution can be shaped to the problem under consideration (Lawler, 1989b). A seasonal sampling frequency will be needed to monitor seasonal bank erosion rates (e.g., Collins and Moon, 1979), but it could equally be monthly to understand intra-annual variation (e.g., Painter *et al.*, 1974) or daily to understand storm-event related variation (e.g., Lo and Wong, 1973).

III Developments in photogrammetry

Photogrammetry has frequently been used nonrigorously to quantify landform change approximately. Rapp (1960) used a series of photographs of Mount Templet, Verspitsbergen, dating back to 1882 to calculate a mean deposition rate on the scree cones of 5.6×10^{-10} gcm^{-2}s^{-1}. Lo and Wong (1973) used an aerial analogue to calculate the magnitude of gully erosion during a single storm event. Using two 35 mm cameras located

vertically above the gully, they calculated that 475.2 cm^3 of material was removed during the storm. Similarly Savage (n.d.) also used an aerial analogue with 35 mm cameras to quantify planimetric information on the Pandatrave Fold in the Cantabrian Mountains, northwest Spain. Painter *et al.* (1974) used stereo-photographs of streambanks to monitor bank erosion rates, in the Cyff and Tanllwyth catchments, Plynlimon and the Coalburn catchment in the north Pennines. Horizontal and vertical scales placed on the banks were used as scale control. Similarly, Collins and Moon (1979) used a series of stereo-pairs of 25 streambanks in the Great Lakes to calculate bank erosion rates. Through an inability to locate permanent targets on the rapidly eroding stream bank, it was necessary to relocate the same camera positions and re-establish the same camera orientations for each epoch. Collins and Madge (1985) used a technique called photoradiation, using single photographs, to monitor a landslide in Cardiff, south Wales. An accuracy of 1:500 to 1:5000 was obtained at distances of up to 150 m. However, although the information obtained from such studies has been useful and they have considered the errors associated with the photogrammetric technique used, they have often suffered from a low level of accuracy. In particular they have failed to allow a full error analysis to be undertaken so that the quality of the spatial positioning of *each* point can be estimated.

1 Photogrammetric principles

To appreciate the nature of a fully rigorous photogrammetric technique, it is necessary to introduce a number of photogrammetric principles. In particular it is necessary to consider the relationship between the three-dimensional object, the two-dimensional representation of the object imaged on the photographic medium (such as the negative) and the 'medium of exchange' or the camera. It is generally assumed by photogrammetrists that an ideal photograph is a special case of a perspective projection (Albertz and Kreiling, 1975; Slama, 1980). That is, a straight line passes between the object point in the object space, the perspective centre of the camera lens and the image point in the image space (line A0a on Figure 2). The basic projective transformation describes the relationship between two such mutually associated three-dimensional systems of co-ordinates (Ghosh, 1988);

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = kM \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix} \tag{1}$$

Where: x, y, z are co-ordinates of point a in the image space; X, Y, Z are co-ordinates of point A in the object space; X_o, Y_o, Z_o are co-ordinates of the perspective centre of the lens in the object space; k is a scale factor:

$$M \text{ is rotation matrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix};$$

$m_{11}..m_{33}$ are elements of the rotation matrix which are functions of ω, ϕ and κ on Figure 2.

This projective transformation can be expanded into the collinearity equations such that for each point on a photograph two equations exist;

$$x = \frac{-c[m_{11}(X - X_0) + m_{12}(Y - Y_0) + m_{13}(Z - Z_0)]}{[m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)]} \tag{2}$$

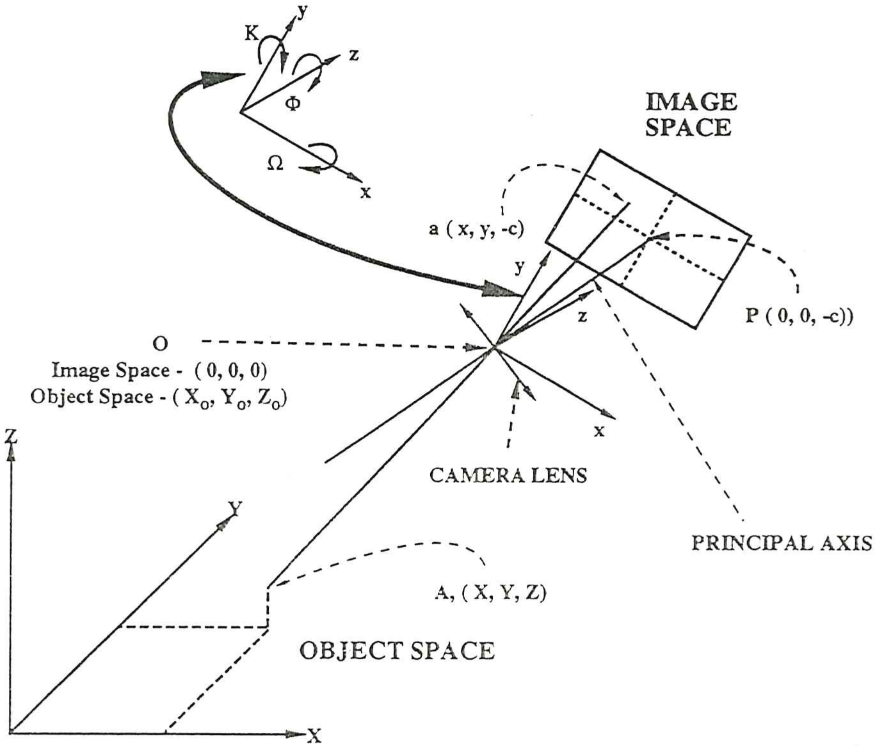

Figure 2 The relationship between points in the object space and image space for an ideal photograph.

$$y = \frac{-c[m_{21}(X-X_0)+m_{22}(Y-Y_0)+m_{23}(Z-Z_0)]}{[m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)]} \tag{3}$$

Where c is the focal length of the camera. Equations (2) and (3) are assuming the special case of a perspective projection, where the value of z can be fixed at the focal length of the camera lens. A perspective projection does not always hold true in physical reality due to disturbances such as lens distortion and atmospheric refraction, in which case the collinearity equations must be extended to model such effects.

In order to determine the co-ordinates of points in the object space, a minimum of two photographs is needed and the parameters in the collinearity equations must either be known or calculated. Essentially it is necessary to consider the camera position in the object space (the object space co-ordinates of the perspective centre of the lens, 0), the camera orientation (the values of κ, ϕ and ω on Figure 2) and the scale factor. The way these parameters are determined can be divided into mechanical and mathematical approaches.

2 The mechanical approach – the analogue technique

Conventional photogrammetry uses the analogue approach, where an analogue plotter is used to recreate physically the spatial relationship between the original camera position(s) and orientation(s) and the ground at a reduced scale. The transformation is achieved and scaled using a series of mechanical operations. The two photographs of the same object must be taken from different positions and they are viewed stereoscopically. A three-dimensional 'stereo-model' is perceived by the operator and, by placing a measuring mark on this scaled model, three-dimensional measurements can be made.

Although rigorous, the analogue approach has two key groups of limitations. Firstly there are limitations on the type of cameras used to obtain the photographic information. In relating points in the object space to points in the image space it is necessary to consider the internal geometry of the camera in use. To define a photocoordinate system in the image space it is necessary to have calibrated fiducial marks in the camera body, whose images are exposed on each photograph either by light entering the lens or by independent illumination of the marks. It is also necessary to know the position of the intersection of the principal camera axis with the image plane (the principal point); the distance of this point from the rear nodal point of the lens (approximately the focal length of the lens); the radial and tangential lens distortion as no lens is optically perfect; and film distortion due to the lack of film flatness at the time of exposure. In photogrammetric (metric) cameras, fiducial marks are included in the camera body which define a photocoordinate system and the position of the principal point. Similarly, the lens is either designed to fulfil the condition of collinearity or is calibrated so that the effects of lens distortion are known. If nonphotogrammetric (nonmetric) cameras are used it is necessary to model the internal distortions mathematically and define a photocoordinate system by other means. In the analogue approach, as it is necessary to reconstruct the relationship between image and object space mechanically, there is little potential for the mathematical modelling of camera geometry. If nonmetric photography is used, errors will be introduced which will inevitably downgrade the level of accuracy in the derived object space co-ordinates. For accurate results using the analogue approach, photographs must be acquired using metric cameras.

Secondly, the analogue method places other limitations because there are optical and mechanical limitations on the orientation of stereo-models using an analogue instrument. For instance, the maximum available tilt movement in an analogue instrument normally restricts the attitude of the camera axes to a maximum of ± 5–6° from the vertical. This clearly limits the approach to situations where the camera axes can be near vertical, notably aerial photography. If it is to be applied to terrestrial situations, either the cameras must be located vertically above the ground surface using some form of gantry (e.g., the aerial analogue of Welch and Jordan, 1983) or the cameras must be orientated so that their principle axes are approximately perpendicular to the area of landform of interest (e.g., Collins and Moon, 1979).

The cost associated with cameras and analogue stereoplotters (Statham, 1990) combined with the inflexibility of project design has meant that fully rigorous applications of photogrammetry have been limited to only a few situations, generally associated with the need for accurate geomorphological information relating to civil engineering (e.g., Wicken and Barton, 1971; Ross-Brown and Atkinson, 1972).

3 The mathematical approach – the analytical technique

The analytical approach overcomes the stringent requirements of the analogue approach through the use of an interactive mathematical model at the analysis stage which greatly enhances the potential for the use of terrestrial oblique images (Kennie and McKay, 1987). With two photographs, a point in the object will give rise to two image co-ordinates or four measurements. If the elements of the rotation matrix and the values of X_0, Y_0 and Z_0 (i.e., the two camera positions) are known, it is possible to calcualte the position of any point with measured image space co-ordinates as there are four equations and only three unknowns.

However, the key advantage of the analytical approach lies in the interactive nature of these equations. Just as by using the measured image position of a point and known camera orientations and positions, it is possible to calculate the object space co-ordinates of a point, so the corollary is true. Using measured image positions of points visible on each photograph that also have known object space co-ordinates, it is possible to determine the elements of the rotation matrix and the co-ordinates of the perspective centre. This can be done using a number of different mathematical solutions, an example of which is the bundle adjustment (Granshaw, 1980). In a bundle adjustment the elements of the rotation matrix and the position of the camera in the object space are estimated in one simultaneous least squares solution. It is not necessary to measure accurately and maintain each camera position and orientation during field survey. A minimum of three co-ordinated points in the object space is necessary, but more points should be provided because redundancy increases reliability of the estimation. These extra or redundant points are used in a least squares estimation to improve the result and to assess the precision of the estimated parameters (Chandler and Moore, 1989). Typically, a conventional field survey is used to establish a network of targetted points visible from both camera locations and to define an object space co-ordinate system. Estimation of the position of each photograph and the rotation of the camera at the time when each photograph was aquired allows the computation of co-ordinates of any other object space points, provided these points are visible on both photographs. Although a minimum of two photographs are needed, stereoscopic vision is not essential if points are well identified on both photographs. However, stereo-viewing increases the number of points that can be co-ordinated by increasing the speed of analysis and because the perception of depth aids object interpretation.

The analytical technique allows a number of important advantages over analogue methods. Most importantly there are fewer geometrical restrictions on the acquisition of photographs, it being possible to use photographs with a significant amount of tilt. Verticals and obliques can be equally analysed for three-dimensional information. Secondly, there are fewer restrictions on the type of camera that must be used to obtain the photographs. The collinearity equations can be extended to incorporate unknown camera parameters (such as the focal length of the camera) and to model such effects as lens and film distortion mathematically (self-calibration). This opens up the potential of using medium format and even standard 35 mm cameras (Chandler *et al.*, 1989), although conventional metric cameras are still preferable as the complexities of photogrammetric restitution are reduced. Thirdly, the output of such studies is digital, generally a set of three-dimensional co-ordinates and is therefore ideally suited to further manipulation either through DTM packages or computer-aided design (see Petrie and Kennie (1987) or Moore *et al.* (1991) for reviews). Classification during data acquisition allow extra information to be recorded automatically with each measured point, such as sediment type at the point of data collection.

IV Analytical photogrammetry as a landform monitoring strategy

In applying analytical photogrammetry as a landform monitoring strategy, it is possible to divide the tasks that need to be performed into two distinct types. Firstly it is necessary to undertake fieldwork that involves the collection of appropriate photographs and corresponding control survey. The acquisition of appropriate photography involves the choice of camera type and camera position. If metric cameras are available, the computational procedure is simplified and generally preferred. However, other conventional cameras can be used and even 35 mm cameras can give acceptable results. Welch and Jordan (1983) used standard 35 mm photography to obtain pre- and poststorm photographs of a stream channel from which the amount of erosion (or deposition) could be determined quantitatively using analytical photogrammetric techniques. Similarly, some consideration must be given to the film type to be used. The acquisition of spatial information from the photographic image is theoretically limited by the grain-size resolution of the film in use, although in practice, the spatial resolution is coarser. The real limit is the precision defined by the bundle adjustment, a product of the network geometry and stochastical properties of both photogrammetric and survey measurements. In practice, the spatial resolution may be reduced further through the inability to identify the same features on both photographs, affected by photographic considerations such as the level of contrast. Camera position can be ground-based or aerial, the ultimate decision being based upon which gives the most appropriate ground cover at the required temporal resolution and the finance available. Thus, if a large area is under consideration or the area is relatively flat, aerial cover is preferred although this is likely to prove expensive. However, if there are good vantage points (such as valley sides in the case of a stream study), then a terrestrial oblique set of images may allow greater operator control over the sampling frequency. This points to a key advantage of the analytical approach; it is possible to design monitoring strategies as required by the nature of landform change under question, rather than being limited by the requirements of analogue photogrammetry. Two camera positions are needed, their optimal location being defined by the parallactic angle and the distance of the sites from the objects under consideration (Figure 3). It is desirable to maximize the sine of the parallactic angle as this increases the precision of the estimates of point co-ordinates and makes precision more homogeneous in space (Granshaw, 1980), but to minimize the distance of the cameras from the objects under consideration. This is reflected in the expression for the weight or degree of reliability of the planimetry of the intersection (P_s) established for vertical photographs;

$$P_s = \frac{\sin^2 \alpha}{d_1^2 + d_2^2} \tag{4}$$

The value of P_s must not be too large, as this implies either very large values of the parallactic angle which may preclude stereo vision or very small values of object-camera distance which may not allow a large enough field of vision. This weighting factor can be expressed in the base distance ratio which is applicable to all types of imagery. It should lie between 0.1 and 0.25 for comfortable viewing but which can be increased up to 0.4 if greater precision is required (Granshaw, 1980). The positions do not need to be fixed such

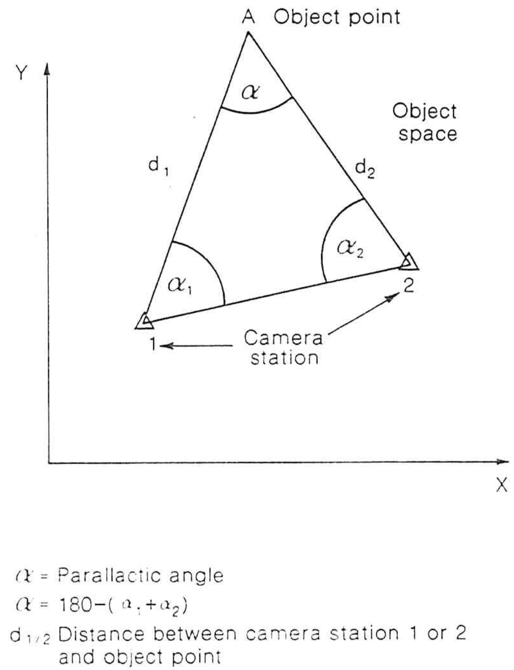

Figure 3 Optimal camera location as defined by the parallactic angle and object distance.

that should the area in which the cameras are located itself become active, relocation of the cameras is possible. This overcomes the problem noted by Ross-Brown (1973) using the analogue approach, where there were problems of tripod stability when a camera base-line was established on point-bar gravels in a stream opposite the eroding streambank of interest.

Before the photographs are taken, it is necessary to ensure that appropriate ground control is established. A three-dimensional object space co-ordinate system must be established and points visible on the photographs must be co-ordinated using conventional survey (e.g., theodolite/EDM or tacheometer). These may either be natural features, although fixed targets are preferable (Chandler and Moore, 1989) and a minimum of three must be visible on both photographs. Provided these targets remain fixed throughout the period of study, only one such survey is necessary, although a second can be useful at the end of a period of study to ensure that any detected differences are not attributable to shifts in the control point co-ordinates. If long-term changes are to be monitored, then means of recovering the three-dimensional co-ordinate system or datum are necessary. It may be appropriate to locate and survey three or four points that are likely to remain in place for the fixed duration of study, even if they are not visible on the photographs. This provides a means of comparing periods of study between which substantial landform change (e.g.,

Figure 4 A current monitoring study; the proglacial stream of the Haut Glacier d'Arolla, Switzerland. Targets are located on stable channel bars. Analytical photogrammetry is combined with tacheometric survey as some zones will not be exposed, and therefore not be visible on the photographs, even at low flows.

landslides) may mean target loss. Figure 4 shows the targets located in a stable section of a proglacial stream in which analytical photogrammetry is being used to study channel changes.

The process of extracting spatial data from the photographs is undertaken in the laboratory and requires access to specialised hardware and software. A number of alternatives are available. The most expensive, large format analytical plotters, are preferable, but are generally only available in photogrammetric establishments. Small format analytical plotters may be a more realistic alternative in terms of cost. Both have on-line facilities where the data acquisition outfit (e.g., stereo-plotter) is in direct communication with the computer system so eliminating the need for human intervention at any stage between initial input and computer output. Even cheaper and more readily available, though less flexible, are stereo-plotters, which are traditional analogue instruments converted into analytical instruments through off-line computer systems.

The first stage of analysis involves defining a three-dimensional co-ordinate system and computing the co-ordinates of targets within that system. The image positions of targets on the photographs are measured and this information is used in a bundle adjustment to determine the camera parameters (positions and rotations) of each camera at the instant each image was acquired. This bundle adjustment should include the stochastical properties of both survey and image measurements. In an on-line device the bundle adjustment is a built-in step but with an off-line device it may be necessary to store such observations in separate files and undertake the bundle adjustment separately. By then measuring the image co-ordinates of new points imaged on two photographs it is possible to calculate the object space co-ordinates of those points. As there is an infinite number of points that can be extracted, some interpretation is necessary, but the output is in digital form and is therefore suited to the production of the digitized terrain model, although it is equally easy to produce maps and plans, profiles and contours, and three-dimensional vectors of strain or movement from sequential surveys. An on-line device shows some intelligence in this respect, in that it is possible to instruct the device as to what form of feature is under consideration, and on the basis of this the device will restrict the operator sampling strategy to point digitization that conforms to the operator's requirement (Stirling, 1982). In the collection of DTM/DEM data, it is necessary to consider the way in which the surface that the heights and elevations represent will be reconstructed. On the basis of whether grid, triangular, radial or contour techniques of surface reconstruction are chosen (see Petrie and Kennie, 1987; Moore *et al.*, 1991), it is possible to direct digitization to the appropriate form of collection. If a triangulation package is available, a combination of regular grid and three-dimensional lines strings (to represent breaks of slope) will provide the most efficient representation of surface form.

These DTM/DEMs have a number of uses. They are clearly necessary both as the boundary conditions and for verification of distributed modelling of landform change. However, their uses go beyond this. Firstly, by comparing information obtained from one epoch with that obtained from the next it is possible to make a direct and quantitative morphogenetic comparison. Chandler *et al.* (1987) used such a comparison to illustrate the growth of a slope toe bulge in an unstable road cutting in Nepal. This could be used to identify preferred zones of water movement and hence predict future zones of instability, a feature which is central to the assessment of landscape sensitivity and therefore the identification of landscape hazard. Similarly Chandler and Cooper (1988) and Chandler (1989) divided a digital terrain model of the Black Venn landslide in Dorset to produce a systems budget. By dividing the model into a series of systems and subsystems, volumes of material could be calculated for each unit. These were used to produce a volumetric analysis of the system components. By knowing the morphological relationship between units in the system, the geomorphologist can begin to understand the complex inter-relationships and feedbacks that exist between them (Chandler and Cooper, 1988). If this can be combined with mathematical models of process then a quantitative evolutionary model may be developed which in theory can begin to predict not only the likely location of future events but also the associated magnitudes.

Secondly, comparison of targetted points on two epochs may be used to provide three-dimensional vectors of specific points, representing the rate of movement, and with a network of such points, the pattern of displacements over a site. This clearly represents a major advantage over conventional methods of monitoring shear effects, such as crack motion detectors. As Erlandson and Veress (1975) note, such methods can provide information in two dimensions at best and often only in one dimension. Thus, Moore (1988) applied analytical photogrammetry to a study of mass movement at Worbarrow Bay, Dorset. Terrestrial metric stereo-pairs were used to monitor small translational mudslides from the beach (Figure 5). In order to determine movement vectors, wooden pegs were used as targets. These were co-ordinated at two epochs and the information was used to compute displacement vectors. Subsequent error analysis revealed that they had a precision of $\pm$ 0.05 m. The retrodictive nature of the photogrammetric approach aids this

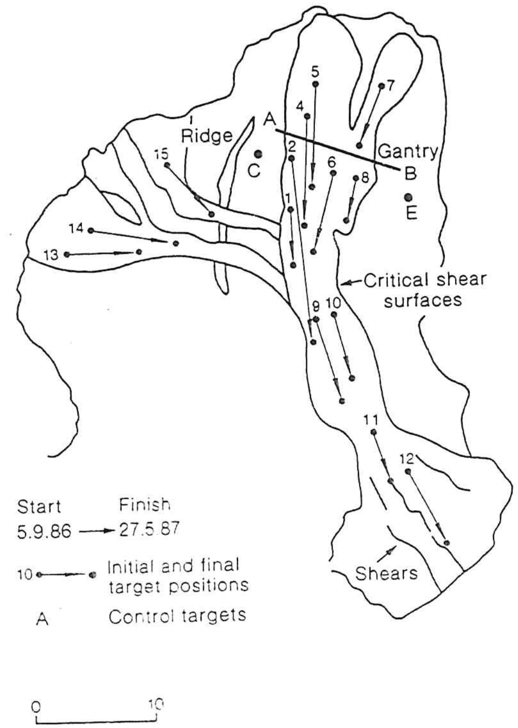

Figure 5 Movement vectors on a small translational mudslide.
Source: Moore (1988).

form of analysis; it is possible to choose points of displacement that are visible on all photographs once a series of photographs spanning several epochs is obtained.

Thirdly, they may be used to provide a measure of process rate. By taking one terrain surface away from another, an integrated measure of process rate is obtained. Conventionally labelled a DTM of difference, it may prove useful in a number of geomorphological situations. For instance, it may provide an accurate measure of the bed-material transfer rate, and potentially therefore the bedload transport rate, if information on subaqueous topography can be provided using other surveying techniques. By taking a DTM of difference away from a consecutive DTM of difference, the geomorphologist is provided with a second derivative of morphological change. Essentially this represents the rate of change of process rate and shows directly those areas of the landscape which, across the period of analysis, are either becoming increasingly dynamic or increasingly stable, and could become a useful predictive tool for the analysis of landform change.

There is one further advantage of the analytical approach in monitoring morphological change. It allows for a full error analysis of the morphological information obtained, a feature not permitted either easily or fully in the case of other landform monitoring techniques. This can be undertaken at the survey design stage, to assess whether the photogrammetric technique is of a scale appropriate to the problem under investigation, or at the analysis stage to provide a full quality consideration of the DTM/DEM co-ordinates obtained. Lawler (1989b) notes that the photogrammetric technique may not be appropriate for some very large and very small rivers. Although the reasons for this limitation essentially relate to problems which the analytical solution overcomes (e.g., the ability to design a photographic survey effectively at an appropriate temporal resolution which is not constrained by fixed camera positions and orientations), the analytical approach also facilitates the assessment at the design stage of whether the technique will provide information on a scale (both spatial and temporal) appropriate to the problem under investigation (Kennie and McKay, 1987). Provided there is basic information on the nature of the terrain in a particular location, it is possible to carry out photogrammetric design a priori in which camera sites are approximately located within the area under consideration. This model can be used to calculate the precision of points within the monitoring site if they were measured through photogrammetric survey. The information obtained provides the basis of the decision as to whether the photogrammetry will provide information during the monitoring period that is of sufficient quality in terms of the magnitude of the morphological change under consideration. Should the approach not provide information of an appropriate resolution, it is possible either to alter the design (such as move the camera positions) or to increase the length of the monitoring period such that the amount of morphological change observed within a particular epoch is increased to a level that meets the spatial resolution of the photogrammetric technique. Thus Fraser (1983), in the Turtle Mountain Study, undertook a premonitoring design optimization with the requirement that the information obtained from photogrammetric analysis should be sufficiently accurate for the monitoring of deformation-related movements of 10 mm or greater. The sensitivity analysis conducted at the design stage indicated that the multiple-point, sub-centimetre movements, between the two chosen measuring epochs, could be detected at the assigned confidence level, thus meeting the main design monitoring accuracy criterion.

Similarly it is possible to undertake a full error analysis of the obtained morphological information *a posteori*. Throughout the stage where information is being obtained from the photographs, it is possible to obtain the variance factor that indicates the likely spatial resolution of the study as a result of the part of the analysis stage completed. These are summarized in the bundle adjustment which allows an 'error ellipse' to be assigned to each observed DTM/DEM point. If the magnitude of morphological change during a particular period lies within these ellipses, clearly the calculated morphological change from a DTM of difference is not significant.

V Analytical photogrammetry and reconstruction of landform change

The analytical approach also opens up an added geomorphological possibility. A key problem in geomorphology is the inability to test theories of landform evolution over large spatial and temporal scales. The discussion in the previous section illustrated the potential for photogrammetry to become part of a more rigorous monitoring strategy, but it may also be the case that the analytical technique opens up a large geomorphological database, stored in the archival photograph. Paine (1985) suggests that the geomorphologist's main problem is that there is insufficient time to observe how landscapes evolve because geomorphological processes tend to operate slowly. Further, in at least some situations, low frequency, high magnitude events are important, but difficult to monitor because the recurrence interval is such that they are unlikely to occur within the period available for monitoring. Traditionally, the geomorphologist has developed mathematical (e.g., Kirkby, 1971) or experimental models (e.g., Schumm, 1977) that can speed up the process of landform evolution, or has drawn upon the ergodic hypothesis, where it is assumed that, in the contemporary landscape, there are landforms at various stages of development. Inferences about changes through time are made on the basis of the variety of forms seen in the present. However there is a fourth approach, made increasingly attractive by the analytical technique. Qualitative measurements of the nature of changes in form have been undertaken using a wide variety of sources for many years. In the coastal environment, changes in spit morphology for instance, have been understood from maps reaching back to the thirteenth century (e.g., Carr, 1962; De Boer, 1969). Similarly Brunsden and Jones (1976) used historical maps of Stonebarrow, Dorset, to establish the sequence of landsliding. Although useful, maps do not fully retain the third dimension, and do not allow the vertical height exaggeration or depth of field associated with a stereo-model, noted earlier as central to landform interpretation. Further, maps show only selected detail, all of which has been subject to human manipulation often for purposes tangential to those of interest to the geomorphologist (Stafford and Langfelder, 1971). Important information of geomorphological relevance is already lost.

Collin and Chisholm (1991) note that many of the most stimulating landform reconstructions necessitate the bringing together photography of all types (terrestrial; vertical; oblique; small format; metric and nonmetric) in an attempt to extract the maximum information from the available historical sources. However, such photography is generally unsuited to rigorous quantitative measurement using conventional photogrammetric techniques. The use of photogrammetry in obtaining accurate quantitative morphological information becomes limited to a small proportion of the near-vertical aerial photographic archive, all terrestrial and aerial oblique images excluded, as well as all images taken with non-metric cameras. However, replacement of the analogue stereo-plotter with the digital mathematical model of the analytical approach, means that although stereo-pairs are still required, they do not have to fulfil the tight rotational and positional requirements demanded by the analogue instrument. Hence the problem noted by Werritty and Ferguson (1980) and Kidson *et al.* (1989) of a wide range of quality in the photogrammetric database is overcome, the key limitation becoming one of availability of archival photographs of the problem under consideration (Stafford and Langfelder, 1971).

The data requirements for the bundle adjustment can be met from two sources. The first possibility is the use of well defined objects and assume that they occupy the same position as when the photographs were taken. Object space co-ordinates can be assigned either by survey or from other sources such as spot heights on old maps. Alternatively, it is possible to undertake a procedure that requires less object space information. The only control requirements that are essential are the minimum necessary for definition of a datum, commonly two planimetric points and three vertical control points (Chandler, 1989). If the collinearity equations (Equations (2) and (3)) are extended to include the parameters necessary to model the internal geometry of the camera then these parameters can be recovered whilst the positions of the photographs are estimated. Such a self-calibration bundle estimation allows the use of photography obtained using nonmetric cameras and archival material taken with cameras of unknown geometric fidelity.

The application of analytical photogrammetry to archival photographs is illustrated by Chandler (1989). Oblique stereo-pairs of Black Venn, Dorset, from five epochs between 1946 and 1988 were used in a rigorous framework to produce digital terrain models which became the basis of further morphological analysis. The resultant grid surface was used to provide information on the distribution of slope angles through time. Clearly, the statistical form of such an output is similar to the characteristic slope distributions of Carson and Petley (1970) for weathered slope debris of different lithological origin (Chandler, 1989) although Carson and Petley's study was based on many fewer observations of individual straight slope sections. Analytical photogrammetry provides a technique that may allow assessment of such a model without recourse to the ergodic assumption. Histograms of slope angle can be produced at differing epochs and then combined to show how the distribution has actually changed through time (Figure 6). Further, through the use of a large number of co-ordinates, the histograms become much more representative of the population from which they are sampled. Chandler (1989) also compared mean slope angles through the 42-year period and noted some evidence of a cycle of activity, although he argued that more time was needed to evaluate this suggestion before the full 100-year cycle suggested by Chambers (1976) and Brunsden and Jones (1980) could be evaluated. A key conceptual finding was that across the 30-year period during which the landslides have exhibited greatest activity, the distribution of slope angle changed remarkably little. Overall slope morphology remained stable despite radical changes in the position of slope boundaries. This clearly reprsents a form of dynamic equilibrium, disclosed by obtaining accurate morphological information through time, rather than hypothesized by modelling or an ergodic approach. The series of DTMs was also used to develop a model of morphological change; by considering a DTM of elevation difference for each epoch, it was possible to obtain a spatially distributed annual rate of morphological change for that period of time. Averaging this out over each epoch provided a spatially distributed mean rate of change for the 1946–76 period. This information was combined with the 1976 DTM to predict the 1988 DTM. Comparison of this prediction with actual observation revealed that 68.8% of the predicted DTM surface was within 3 m of the observed surface. The 1946–88 rate of change and the 1988 DTM then became the means of predicting of predicting the DTM for the year 2000. This example shows how a DTM series can be extrapolated through time to provide a basis for forecasting landform development. However, the extrapolation is purely empirical. A real area for future combination of photogrammetry and geomorphological theory is in extrapolation using realistic process equations as well as a continuity equation. The ultimate objective of the study illustrated in Figure 4 is the development of a model that can predict topographically induced flow acceleration and deceleration based upon realistic process equations and the equations for continuity of mass and momentum. This will become the basis of a model to predict sediment transport and associated channel change. In turn, the new topography will become a boundary condition for the next iteration.

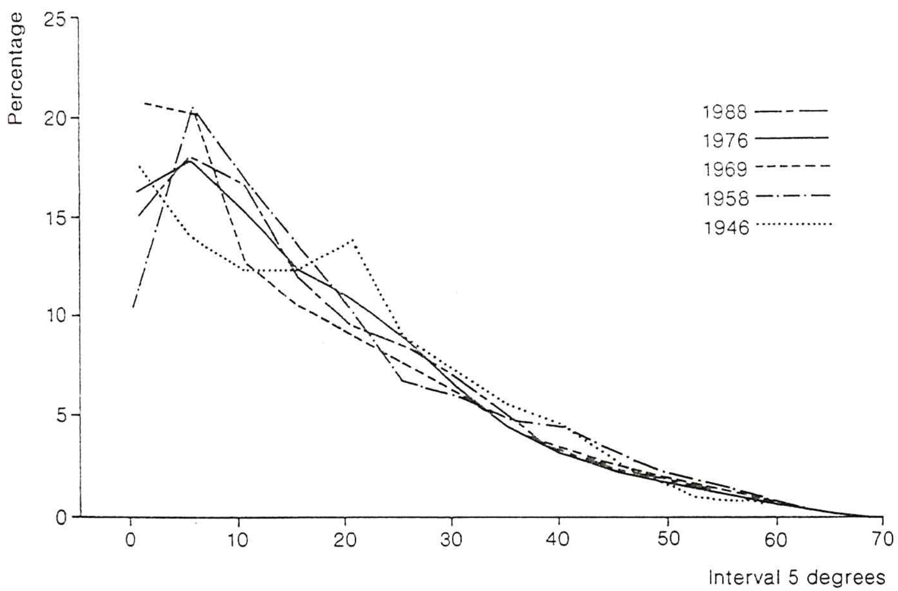

Figure 6 Histograms of Black Venn slope angles measured using archival photogrammetry.

VI Future developments

Developments within photogrammetry increase the flexibility of its use as a geomorphological tool. In terms of dynamic environments, the use of photography to monitor landform change may allow morphological information to be obtained at a spatial and temporal resolution that matches the rate of landform change and in a form ideally suited to further manipulation. Such information becomes central to both the estimation of process rate and ultimately to the development of process-based models that predict changes in landform.

In terms of the analysis of archival photographs it is important to appreciate that the photograph represents an example of an incidental measurement (Brunsden and Thornes, 1978), that is one made at a point in time without consideration of the frequency of observation required for the surveyed subject and often for a purpose other than that finally employed by the geomorphologist. Developments in the analytical approach clearly help to overcome the unsuitability of purpose, but they cannot overcome the problem of temporal sampling. Extreme care must be taken when inferring the nature of landform change from incidental observation when there is no continual observation of that change. Stafford and Langfelder (1971) had just this problem in a beach monitoring study. Each archival photograph recorded beach location and condition at one sample point of the transient beach location, even though beaches are known to undergo cyclic seasonal changes and are also sensitive to environmental conditions and factors such as storms. This may imply the need to build up geomorphological photographic archives, where photographic sampling is informed by geomorphological knowledge. It can take as little as a day to install the necessary photogrammetric project design and obtain appropriate photographs, information which can be stored and analysed in retrospect to produce DTMs, should the need for accurate historical morphological information arise. The measurement of real morphology and real morphological change should become an integral part of any geomorphological study.

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Seed banks as a neglected area of biogeographic research: a review of literature and sampling techniques

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Abstract: The article highlights a comparatively neglected area of biogeographical research – seed banks and the distribution of seeds in the soil. The article reviews some of the relevant literature on seed banks and the methods for their study. Attention is focused on aspects of seed banks of particular relevance to biogeographers, with detailed examples drawn from seed bank studies in both temperate and tropical environments. In the review of the seed bank literature, the topics covered include the seed banks of successional communities and the size of seed banks in different vegetation types. The species composition of seed banks in different plant communities is discussed, particularly the degree of correlation between the species composition of seed banks and associated ground flora. The relationships between seed persistence, depth of burial in the soil and soil properties, such as moisture and pH, are explored. Seed bank heterogeneity is examined and a number of studies which have attempted to describe and measure the spatial variability of seed banks are summarized. Ways of classifying seed banks in terms of seed bank strategies are explained. The role of seed banks in conservation is discussed, for example in restoration projects, where preferred species have been lost from the vegetation but survive in the seed bank. The relevance of seed banks for the conservation of rare species and in landscape management is considered. Lastly, the contribution of seed banks to the recovery of vegetation following disturbance in various plant communities is discussed. In the review of seed bank sampling techniques, the subjects considered include methods of sample collection, the sampling intensity required for reliable estimates of seed density, a consideration of the relative merits of random and systematic sample distribution, as well as the importance of the timing of sampling. Various methods for the estimation of seed numbers in samples are appraised; these either involve extraction of seeds from the soil, followed by seed identification or enumeration by germination and seedling identification. Problems of analysing seed bank data are considered and several useful techniques for data analysis are suggested. Finally, the article draws attention to areas of future seed bank research for biogeographers and plant ecologists.

Key words: soil seed bank, buried seed, sampling, biogeography.