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ATTRIBUTES OF DRAINAGE BASIN TOPOGRAPHY : AN EVALUATION OF PROFILE AND ALTITUDE MATRIX APPROACHES AND THEIR HYDROLOGICAL RELEVANCE

Sarah Ann Bell
Graduate Society

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ABSTRACT

ATTRIBUTES OF DRAINAGE BASIN TOPOGRAPHY : AN EVALUATION OF PROFILE AND ALTITUDE MATRIX APPROACHES AND THEIR HYDROLOGICAL RELEVANCE

A program in FORTRAN, SLOPROFIL.2, was written to construct contour orthogonals with constant steplengths from a square grid of altitudes, using a surface model provided by cubic weighting functions operating on four overlapping quadratics. The validity of this program was established by comparing computer profiles with the same profiles measured in the field. Summary statistics of land form attributes from computer profile samples were compared with those for the same attributes sampled systematically by the program G. The latter results form a yardstick for judgement of the representativeness of surface coverage by computer profiles, which can be optimized by changing profile terminating conditions input to SLOPROFIL.2. The minimum size of profile sample necessary for representative coverage could also be determined.

Altitude matrices were made and field profile surveys undertaken in the 27 km^2 Gara catchment (South Devon) and the 1.3 km^2 Netherhearth catchment (Upper Teesdale). The computer profiling method was also applied to the 118 km^2 Ferro catchment (Southern Italy) to investigate the broader applicability of the method. In the first two cases, sample sizes of 20-30 profiles were found necessary; in the third, nearer 100.

Various sampling schemes for locating profile points of origin were investigated : points on a grid, points spaced equally along the Profile Sampling Baseline (PSBL), and points located along divides and talwegs. The grid scheme gave most complete surface coverage; a PSBL needs to be taken far up into valley heads to enable these areas to be sampled.

Use of computer profiles carries many advantages, including explicit and objective consideration of terminating conditions, inclusion of the hydrologically important slopes which are NOT straight in plan, and speed of execution. It is recommended that geomorphologists establish a profile sample on computer in this way prior to field survey. Various hydrological applications are also proposed.

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CHAPTER 1 : INTRODUCTION

1.1 Overview

1.2 Slope profile survey

1.3 Land form data from altitude matrices

1.4 Theoretical background to the importance of topography for hydrology

1.5 Hydrological modelling

1.6 Structure of thesis

1.7 Notation

1.1 Overview

> '... a beach ... is not merely a seaward slope, it is also a surface across which material is transported. It is, therefore, possible to view the morphological system of a beach in two ways : as a series of variables relating to profiles at right angles to the coastline; or as a set of attributes relating to points upon a continuous surface. Somewhat different variables are likely to prove important in each case ....Obviously the second approach will give a much more detailed picture of the composition of the beach, while the former is concerned to link the foreshore to the other major classes of slopes in the landscape.' (Chorley and Kennedy, 1971, 60-61).

This research is concerned with the interaction of the two approaches to land form measurement featured in the quotation above : by linear and by point-based sampling. In focussing on the kinds of attributes measurable using either approach, comparisons can be made between them to the advantage of both. The context of the work is the drainage basin, a subject of much research in geomorphology and hydrology.

This work is conducted within the field of general geomorphometry, defined by Evans as 'the measurement and analysis of those characteristics of landform which are applicable to any continuous rough surface ....General geomorphometry deals with surface altitude, gradient, distance and area ....as a whole [it] provides a basis for the quantitative comparison even of qualitatively different landscapes, and it can adapt methods of surface analysis used outside geomorphology' (1972,18). The central aim of the research is to evolve ways of sampling a land surface by slope profiles to give a set of measurements of land form properties whose summary statistics are similar to those from a systematic sample of point measurements taken over the entire area of interest. Slope profile survey is a method much used in geomorphology; by contrast systematic point samples derived from altitude matrices have up to now received more attention outside the discipline. These two sources of

geomorphometric information are defined and discussed further in sections 1.2 and 1.3.

This research is considered important for the many process models in geomorphology that require detailed topographic inputs. At present there is a lack of knowledge on how to generate a pattern of slope profiles in an area to give measurements which represent the entire area in the sense defined in the previous paragraph. This lack of knowledge is largely due to the absence of a means of gauging the degree to which profile measurements have achieved this sampling aim. In this research altitude matrices are used as the yardstick : thus the two methods are used not in competition but to complement each other.

One important criterion in this work is to use efficient methods for gathering the data for input to a process model in which topography is likely to form just one of many geomorphic phenomena to be sampled in space. For this reason most of the altitude matrices constructed were derived from maps rather than by fieldwork, and therefore could not yield the detailed topographic information obtainable in the field. Thus field profile survey is needed to supplement matrix-derived information : this is the other side of their complementarity. The influence of measurement resolution on results inevitably constitutes an important secondary theme in this research.

The focus on drainage basins is due to their validity as functional as well as morphometric units in humid temperate regions. The class of models whose requirements for topographic information are given most consideration in this thesis are hydrological models, which are generally formulated for drainage basins. The reasons why hydrological models need the sort of topographic information produced in this study are outlined in sections 1.4 and 1.5. The approach could however be applied to other

morphometric units and other process studies, and throughout the thesis emphasis is on methods employed rather than exclusively on results for the particular catchments studied.

Section 1.6 contains an outline of the thesis.

1.2 Slope profile survey

'A hillslope profile is a line on a land surface linking a crest on a drainage divide and a base on a drainage line, following a maximum gradient path which runs perpendicular to the contours. The idea of hillslope profiles is most easily applicable in well integrated fluvial topography, but has some relevance in most kinds of landscape.' (Cox, 1981, 62).

The method of profile measurement originated within geomorphology : it was pioneered by Savigear (1952) who found a spatial sequence of cliff profiles in South Wales which could be taken to represent a temporal pattern of slope development following cessation of active erosion at the base. Since then geomorphologists have acquired considerable experience in profile survey and there are accepted guidelines for the method, many of which have been set down in the British Geomorphological Research Group's Technical Bulletin 'Slope Profile Survey' (Young, 1974). Survey of a profile proceeds up or down a line orthogonal to contours as a series of pairs of measurements of angle and ground surface length, the latter being held constant at a recommended length of 5 m (ibid., 32).

The consensus is that this method should be rapid and economical in execution rather than designed to yield precision measurements (as is the case in civil engineering surveys for example). Rapp (1967) summed up these requirements of economy in profile survey : measurements of

slope angle should be accurate to within $\pm \frac{1}{2}°$; it should be possible to measure a slope 50-300m high and up to 35° in gradient in not more than 3-4 hours; and no more than two surveyors should be involved. Although there is broad agreement on method of measurement of profiles, the way to sample a landscape of interest by a set of profiles has been comparatively neglected in the literature. The 1974 Technical Bulletin's recommendation on this is to site profile points of origin along a Profile Sampling Baseline (PSBL) constructed half-way between divides and talwegs, from which profiles can be surveyed up to the crest and down to the talweg. However it is not clear how complete a coverage of the terrain could be achieved by profiles constructed in this manner, and the proposition that bias in areal coverage by profiles is minimized by this scheme has not been tested. Such a course of action will be pursued in this research.

The lack of attention to spatial sampling in much of the literature on slope profiling is a result of the common use of profiles to elucidate evolution of form, as was done by Savigear. For this type of study, geomorphologists tend to require a few particularly distinctive profiles, that on analysis can be divided into a series of components of constant angle or curvature, with relatively sharp breaks in between. This process of 'atomising' hillslopes (Cox, 1978) has been encapsulated in computer programs (Ongley, 1970; Young, 1971), but these highlighted rather than disposed of the subjective nature of the decisions that must be made in splitting what is often more continuous than discrete, and their results have been unsatisfactory (Cox, 1979).

In this research, attention is focussed on slope profiles as terrain sequences followed by mass and energy on slopes under the influence of gravity, and on slope profile survey as a spatial sample of such sequences in a drainage basin. The lack of concern in many slope studies

for even spatial coverage of profiles is illustrated by the frequent restriction of measurement to 'slopes relatively straight in plan' (Young, 1974, 14). This means avoidance of areas in the landscape having appreciable contour curvature, such as valley heads. Yet such areas of convergence of flow are vital to hydrological studies and very important geomorphologically. Several studies have suggested that drainage basins be divided conceptually into valley head and valley side zones : for example Marcus (1980), who finds that relationships among morphometric variables are weaker in the former zone due to lack of the unifying influence of a fluvial channel. The many studies of the East Twin catchment in Somerset (e.g. Weyman, 1974; Finlayson, 1978) have all recognized two process domains in that basin : an upper headwater of concave contours, and a lower v-shaped valley section. In order to sample valley head areas by profiling, it is necessary to have a method of measuring slopes not relatively straight in plan; it became clear during the field survey undertaken for this research (chapter 2) that there are fewer guidelines for this in the literature.

The task of achieving a spatially representative sample has been found to be an arduous one in slope profiling by Parsons who concluded that 'very intensive sampling is required if values are to be obtained that adequately reflect average conditions of form for a drainage basin as a whole' (1982,77). Cox has stressed qualitative rather than purely quantitative difficulty : 'Selection of a set of paths on a surface is a special kind of sampling problem which is not well understood. Any kind of point set selection ... ideally should be accompanied by a demonstration that the point set is associated with a representative profile set : it is not sufficient that the point set be chosen representatively' (1981,62). Evans proposed that 'it is inherently impossible to produce a set of surface-specific lines (slope lines) which is an

unbiased representation of an irregular surface. Though of great interest in themselves, slope profiles are poor in representing the surface of a region' (1979,18). This research will evaluate several profile sampling schemes, including Young's PSBL, and comment on Evans' suggestion.

Parsons, in the study quoted from above, quantified twelve 'slope profile attributes', including total length, height range, curvature, average slope, maximum slope, number of changes of curvature direction,and mean angular difference between adjacent segments. These will be important to some process studies, and the fact that such measures can usefully be profile-based is a powerful reason for retaining profile measurement. The argument of this thesis is that the basic data yielded by profile measurement - e.g. gradient, and profile curvature (calculated from the spatial sequence of gradient) - should be compared with similar general measurements that can be made from a different source (matrices), to establish the success with which profiles cover the area of interest. Once this has been satisfactorily achieved, specific indices can be calculated from the profiles with more confidence about their validity over the entire area of study.

Many geomorphologists have followed Strahler (1950 a & b) in taking maximum rather than mean angle from measured profiles to be used in analysis. However the former has been shown to be influenced by the measured length used in field profile survey (Gerrard and Robinson, 1971). An objection put forward by Kennedy (1969) to use of mean slope angle is that different estimates of it are likely from field and map studies. She argued that in the field, it is rational to terminate a profile near a plunging divide where the latter's angle of plunge equals the gradient of the profile; but in map analysis such a point is less easily identified. As a result map studies will tend to yield

lower estimates of mean slope angle because a greater length of low-angled interfluve will have been included in measurement. In this study, where maps have been converted to altitude matrix form, a more objective definition of the termination of a profile is possible. An aim is to promote greater comparability between map and field studies, using moment-based statistics rather than extremes of land form attribute frequency distributions.

Another argument for the incorporation of comparisons with surfaces into profile studies is that too often the latter have ignored the third dimension in landscape. There is commonly an assumption that a slope orthogonal can be taken to represent the flowline of mass and energy down a hillslope, without consideration of this line's relation to other such flowlines. Yet information on the third dimension is vital to many process studies, including hillslope hydrology where the concentration of soil water flowlines in areas of concave contours is frequently observed to promote soil saturation and rapid slope discharge (e.g. Anderson and Burt, 1978a). Evolutionary slope studies too are not justified in ignoring the third dimension : thus Armstrong (1976) found in a simulation of landscape development that slope orthogonals shifted in plan position over time. Carson and Kirkby (1972) however attested that orthogonals settle to an equilibrium position during evolution. Culling observed that 'The genesis of the landscape cannot be said to be understood in any fundamental way unless the evolution of the component landforms can be analysed and predicted in three dimensions' (1963, 153).

It is possible to supplement profile surveys with measurements of contour curvature during fieldwork, but this considerably slows the measurement programme, and for these measurements to be possible a band of ground extending for at least 20m on either side of the profile

path must be undisturbed and accessible, which causes difficulty in some parts of natural drainage basins as was found by Parsons (1979). Alternative methods of gathering this type of data merit serious consideration.

1.3 Land form data from altitude matrices

A digital terrain model (DTM) has been defined as 'an ordered array of numbers that represents the spatial distribution of terrain characteristics. In the most usual case, the spatial distribution is represented by an XY horizontal coordinate system and the terrain characteristic which is recorded is the terrain elevation, Z' (Doyle, 1978, 1481). An altitude matrix is a type of DTM whose altitude (Z) values fall at the intersection points ('vertices') of a rectangular grid in the horizontal plane. The matrices to be used in this thesis all have vertices on a square grid : in the notation established above, $\Delta X = \Delta Y$ = a constant, known as the grid mesh or horizontal resolution of the matrix. The Z data generated and used in this research are stored on computer in rows starting at the upper left-hand ('north-west') corner of the map (vertex X = 1, Y = 1); this convention and the unvarying grid mesh (which must always be stated) mean that individual X and Y coordinates need not be stored.

It is certainly the case that results obtained using DTM's are very dependent on their grid mesh size as well as on the ruggedness of the terrain being sampled. There is controversy as to how to express the accuracy of a DTM : root mean square (RMS) error of DTM Z values can be established by comparing a sample of them with the parent population, but several authors have pointed to the lack of guidelines on how faithfully a morphological feature should be portrayed (e.g. Ackermann, 1978). An answer relevant to this research is linked to the

(hydrological) focus of the work and is indicated by the following quotation from Anderson and Burt: 'The pronounced downstream component, apparent on both the flow net...and the soil water potential maps ...demonstrates the importance in any physical model of correctly incorporating the orthogonal slopes of stream channel and hillslope, since most hillslope hollows have a significant downstream basal gradient superimposed on the convergence phenomenon discussed' (1978b, 1128). Much attention in later chapters of this thesis is focussed on defining and evaluating paths orthogonal to contours drawn through a matrix, by comparison with field-surveyed profiles.

It is by no means universally accepted that a square grid is the most efficient or accurate for a DTM. 'Topographic surfaces are non-stationary ....A regular grid therefore has to be adjusted to the roughest terrain in the model and be highly redundant in smooth terrain' (Peucker et al, 1978, 518). With coarse matrix mesh sizes there is the danger that highs and lows in the landscape will be generalized out as these localized features slip through the sampling net. The case has been put forward for sampling of surface-specific points (peaks and pits, passes, ridges, course lines, and breaks of slope - Mark, 1975) to form an irregular network of points stored as a set of X,Y and Z coordinates together with pointers to their neighbours in the net, forming a Triangulated Irregular Network (TIN).

In a study by Olender (1980) the efficiency and accuracy for various military tasks (visibility, trafficability) of regular grid matrices at various mesh sizes were compared with TIN DTM's. Olender was unable to conclude firmly in favour or against one or other of the types of model because in the 'multiple important measures of performance' no one type consistently out-scored the other. For each study area, Olender constructed one TIN to be compared with several mesh sizes of regular grid,

and he concluded that it would be revealing to compare several TIN's of the same area having different point densities, to be comparable with the range of resolutions of grid DTM tested. He found that the densest regular grid nets were more accurate than wide nets, as expected. Also for TIN models, results from areas where numerous TIN points were required to capture many peaks, pits, passes, etc, were superior to those for areas where fewer TIN points needed to be generated in this way. This implies that TIN accuracy depends similarly on point density. The important advantage of a regular grid DTM is that point density is constant and can be stated, whereas that for a TIN is not. Olender's finding suggests that use of the latter type of DTM introduces an element of incompatibility when making comparisons between TIN's for different areas. Grist and Stott reached a similar conclusion on the importance of point density in comparing grid and string (digitized contour) DTM's for an engineering application : 'despite the different relationships between errors and densities of points, all the models produced closely similar estimates of the volumes of earthwork when used with the highest density of points' (1977,35).

Square grid DTM's are becoming increasingly available as part of the process of orthophoto production and there is much awareness of their potential, particularly in the field of cartography. Kelly et al claim that software development on the Gestalt photomapping system 'should soon make it possible to merge DTM's to form digital models for large areas : such models will ultimately be referenced by computers much as maps are by men' (1977, 1416). The problems of interest to many people in digital cartography therefore revolve around the best way of using altitude matrix data that they already have, rather than whether to make an altitude matrix or some other type of DTM. By using altitude matrices, this research was able to take advantage of widely-available

computer packages designed to output or input data on a rectangular grid, such as the General Purpose Contouring Program (Calcomp, 1973, 1974) and Harvard University's SYMVU (Muxworthy, 1972). Square grids make for easier computation in surface-fitting because their orthogonality means that matrix inversion is not required (e.g. Davis, 1973). According to Collins and Moon 'The square grid DTM is a format that is most suitable for computer operations' (1981,76).

A suggested way of minimizing redundancy of points in areas of a grid DTM having more uniform terrain, is to sample a basic square grid at low resolution (large spacing between grid points) and then resample certain patches of the DTM in more detail if second differences between sampled points exceed a chosen threshold value (Makarovic, 1973). This method was devised with semi-automated data capture from stereoplotters in mind, but since only manual methods of tracking map data were available to this researcher (as is likely to be the case for many geomorphologists), it was judged to be quickest to pass through the data capture stage only once.

The use of a square grid means that altitude matrices are analogous to profiles measured with constant ground surface lengths as is the recommended procedure (section 1.2); with a matrix it is the horizontal length which is held constant.

A potential hazard of gridded altitude data which has received attention in the literature, is that the (constant) sampling interval could equal a topographic periodicity in the landscape, and in that case an incomplete picture of surface variability would be provided by the matrix. For regular micro-features (e.g. defined as having a wavelength smaller than 64 feet by Stone and Dugundji, 1965), such as dunes, there is this danger; but at the scale of drainage basin topography this is unlikely, as is illustrated by a quotation from Craig: 'there is no

advantage and considerable increase in complexity if we adjust the orientation to a particular perceived structural pattern or topographic "grain" since we either eventually get off the pattern for which adjustment was made, or we must change orientation and thus lose the space-filling properties! We can therefore assume a grid orientated north-south and east-west' (1982,111). Ley dismissed the problem: 'A systematic rather than a random sample of points was chosen as the author believes that the concept of wavelengths in relief is meaningless' (1981, 30).

DTM's have been analysed in various ways to investigate land surface form. One study that has received much attention is that of Greysukh (1966), who encouraged the identification of forms such as slope, ridge, valley, knob, sink and saddle, by a sequential circular search of the neighbours of a point, incorporated into a computer program by Grender (1976). To obtain numerical values of land surface attributes from matrices, however, it is necessary to interpolate between points in the DTM. If gradient is calculated for a grid intersection ('vertex') of a matrix by comparing its altitude with that of its eight neighbours, for example, and choosing the pairing which maximizes altitude difference, two assumptions have been made. The first assumption is that linear interpolation is appropriate between vertices; the second, that it is not too great an abstraction from reality to restrict aspect to only eight directions of the compass. Algorithms of this sort exist, but are not sophisticated enough for the purpose of this study, where accurate definition of slope aspect is required.

A more advanced algorithm is incorporated in the terrain analysis program to be used extensively in this research. This program, 'G', was written by M. Young to the specifications of Evans (1979,1980,1981).

It fits quadratic surfaces by least squares to sets of 3 x 3 vertices in an altitude matrix, taking first and second derivatives at the central point of each of these local fits to generate values of gradient, aspect,and profile and plan convexity in addition to altitude. Each vertex in the matrix is in turn made the centre of such a local surface, allowing the attributes to be calculated for every matrix point (with the unavoidable exception of a border around the matrix one vertex thick, where points lack a sufficient neighbourhood for surface-fitting). The procedure is explained in Young (1978) and more details appear in chapter 3 of this thesis. Evans maintains that the program permits 'effective multivariate comparison of different areas' (1980, 294).

In this research the link between profiles and matrices will be effected via a program, SLOPROFIL.2, especially written for this study to draw contour orthogonals through matrix information. Given this requirement, an altitude matrix provides a much better data source than digitized contours, on the evidence of Evans (1972) who cites and illustrates an attempt by Piper and Evans (1967) to construct contour orthogonals from points equally spaced along digitized contours. This produced unacceptable results in areas of contour curvature. To this author's knowledge, SLOPROFIL.2 is the first program to have been written with the purpose of producing complete slope profiles from a DTM : the hill-climbing routine reported by Moore and Thornes (1976) is a simpler algorithm adequate for the restricted purpose for which they used it, to determine upslope distances for use in the Universal Soil Loss Equation.

SLOPROFIL.2 uses an approach similar to G's in that it starts by fitting quadratic surfaces to 3 x 3 vertices of a matrix; however further fitting procedures are then required to ensure continuity of the surface across the numerous boundaries between quadratics. The

derivation of the program will be explained in detail in chapter 4.

In general altitude matrices and other DTM's have not been much used by geomorphologists. This must be partly because the narrowest mesh size justifiable for matrices made from common map scales (about 50m mesh from Ordnance Survey 1:10,000 and 1:10,560 maps, see chapter 3) is not considered detailed enough for geomorphological studies, while field survey of a matrix is (rightly) thought of as time-consuming. Geomorphologists are also more accustomed to the sort of morphometric information yielded by profiles (some examples from Parsons' work were listed in section 1.2) than to altitude and its derivatives calculable from an altitude matrix using G. An aim of this research is to show that realistic profiles can be generated from matrices made at the sort of mesh sizes that it is possible to construct using commonly-available Ordnance Survey maps. The relative ease of constructing profiles on computer rather than measuring them in the field will enable this research to investigate the coverage of a land surface achieved by various profile sampling schemes as profile numbers are allowed to become very large.

1.4 Theoretical background to the importance of topography for hydrology

Much interest is focussed on high peak flows which occur during or shortly after large storms. This type of flow can be called quick flow (Hewlett and Hibbert, 1967), to be distinguished from delayed flow which sustains the stream during periods between storm runoff events - although the precise separation of the two types of flow on a hydrograph is always arbitrary. Hewlett and Hibbert recognize this arbitrariness but also argue that it is informative to rank catchments according to the amounts of quick flow that they generate; these authors separate quick flow from the rest of the hydrograph by projecting a line from the

start of the stream rise at the beginning of a storm on a slope of $546cm^3/sec/km^2/hour$ until it intersects the falling limb of the hydrograph following that storm. Using this technique, they calculate that approximately 10% of precipitation, or 23% of the total water yield by streams, in the Eastern United States is quick flow. Thus quick flow is not the dominant contributor to flow volumetrically, but interest focusses on it in hydrology because of its potential to cause flooding, and in geomorphology because of the large amount of geomorphological work often achieved by events of lower frequency and higher magnitude than the average (e.g. Wolman and Gerson, 1978; Newson, 1980).

It is commonly argued that quick flow must have reached the channel by running over the ground surface, since rates of overland flow are at least two orders of magnitude faster than 'matrix throughflow' (subsurface flow between soil particles)(e.g.Weyman, 1975,18). However several workers, most notably Hewlett, have argued for the importance of sub-surface stormflow, which 'refers to that portion of the stream's lateral inflow that is derived from water that infiltrates the surface and moves laterally through the upper soil horizons toward the stream channel as unsaturated flow or as shallow perched saturated flow above the main groundwater level' (Freeze, 1974,629). Such flow may supplement overland flow in runoff peaks by a 'translatory' mechanism whereby new infiltrating rainwater forces older water already in the soil towards the channel (Hewlett and Hibbert, op.cit.). It is certainly common for a throughflow peak to follow closely behind a more short-lived rise due to overland flow, and contribute the majority of the runoff volume attributable to the storm event (e.g. Troake and Walling, 1973; Anderson and Burt, 1978a). Mosley (1982) argued reasonably that the ability of a parcel of subsurface water to contribute to stormflow depends on the length

of slope it must traverse: for example, if all the slopes in a catchment are less than 30m long, a large proportion of the subsurface flow in that drainage basin could be expected to contribute to its storm hydrograph.

More recently, another subsurface route for quick flow has rightly gained attention : that of natural underground pipes (Gilman and Newson, 1980; Jones,1981). These may collect surface or subsurface water from saturated areas of the catchment far away from the main channel, and conduct this water to it through possibly unsaturated areas, at rates similar to those of open channelled flow. Other workers (e.g. Whipkey, 1967; Eyles, 1968; Arnett,1976) have concluded that soil water moves preferentially along macropores when saturated conditions exist, such structures being promoted by plant roots and burrowing organisms in the soil. These pores need only be a few tenths of a millimetre in diameter (Mosley, op.cit). This complexity on a very detailed scale is a fact of life in hillslope hydrology and should not be allowed to deter those who seek to model at a drainage basin scale, because 'the effects of soil variability and the presence of different flow paths are integrated over an area, so that a rather simple hydrograph form results from the interaction of a highly complex system of flow paths' (ibid,89).

A number of mechanisms for producing surface runoff are now recognized by hydrologists and geomorphologists to have validity in different parts of the world and even in the same catchment at different times or places. The consensus is that Hortonian (infiltration-excess) overland flow is rarely produced over wide areas in humid temperate regions well covered with soil and vegetation, although local areas of reduced infiltration capacity such as paths and tracks may generate this type of runoff. The observation that overland flow is usually produced in restricted source areas in topographic lows rather than as a uniform sheet of water over a whole catchment, was one reason why the Horton

model was overturned as a dominant explanation of runoff in humid and well-vegetated areas. Betson (1964) found that runoff occurred on average from only 4.6% of the watershed area, concluding that 'The effective runoff-producing area of a watershed ... is not the same as that delineated by the topographic divide' (ibid,1548). The other significant finding was that water that had infiltrated into the soil was not the dead store that Horton had envisaged, but could flow laterally (Hewlett and Hibbert,1963; Whipkey,1965) between storms to provide 'a primed zone along the channel for quick release of water during storms' (Helvey, Hewlett and Douglas,1972).

It is a common observation that low-lying areas adjacent to a channel become saturated during a storm and rain falling on them runs straight to the channel as saturation overland flow. According to Dunne, saturation is brought about where the water-table lies not far below the ground surface, so that infiltrating rain water can quickly raise it to the surface. He therefore stresses the importance of slopes concave in vertical section near their bases, where the ground surface literally dips towards the water-table, in promoting this type of runoff (Dunne, 1978, 271).

Other workers attribute the same phenomenon to the rise of a perched water table in the soil, which is fed by subsurface water that has been forced by the presence of less permeable soil layers with depth to flow roughly parallel to the soil surface rather than vertically downward. It is common to find a more permeable soil horizon at the ground surface, a phenomenon encouraged by ploughing; indeed some authors have argued that such a 'transition' layer is ubiquitous (Zaslavsky and Sinai, 1981).

The flow paths of this near-surface flow are predominantly orthogonal to contours, so that contour curvature exerts a strong

influence on them, to produce a situation on hillslopes similar to that hypothesized by Hack and Goodlett : 'If the ground were imagined to be an impervious, smooth surface lacking any channelways, the amount of runoff crossing any place during a rain would be proportional to a function of the radius of curvature of the slope contour' (1960, 6). Such flowpaths converge on hollows and diverge over spurs : the two authors found one hollow which they calculated to have a drainage area two hundred times as large as that of the adjacent sideslope, in their Central Appalachian study area. They also found a close relation between the distribution of moisture-loving plants and topographic hollows, concluding that not only surface but also subsurface flows concentrated in contour-concave areas.

In areas of gentle slopes (e.g. 6°), the soil water potential pattern may be able to distort somewhat the flow dictated by topography alone (Anderson and Kneale, 1980), since water in soil flows from areas of high to low total potential and total potential = elevation potential + soil water potential. Many upland catchments have slopes steeper than 6° however, so that the elevation potential term in practice dominates the total potential equation, as at Bicknoller in the Quantock Hills in Somerset (Anderson and Burt, 1978b).

By concentrating subsurface runoff, hollows become more efficient at producing discharge whether or not they actually stimulate production of saturated overland flow, because hydraulic conductivity of the soil increases up to saturation. Anderson and Burt found at Bicknoller that 'the hollow zones, though only 45% of the slope area, produce at least 58% of the total discharge - even at a time when spur discharge is at its greatest ....Thus convergent flow seems to be a more efficient mechanism for draining a slope than the divergent flow found on spur zones : the formation of a saturated wedge in a slope hollow means that

the discharge generated is proportionally much greater than the area of slope drained by the hollow '(1978b, 1130). In systems terms, topographic hollows provide a positive feedback situation for the production of hill-slope discharge.

The contrasts between the water-table-rise and subsurface-throughflow schools of thought on saturated overland flow production are not as important as their similarities : both stress the tendency for saturation to build up during a storm in localities which drain a large area of slope and are therefore likely to have high antecedent moisture contents. In the Dunne model concavity in profile is held to accentuate this effect; in the Hack and Goodlett model concavity in plan is important. Such areas will contribute to quick flow in a stream hydrograph if their location permits them to discharge water quickly into the channel, either by close physical proximity or by access to a pipe. During a heavy storm, saturated conditions expand into other areas made 'hydrologically sensitive' by topography and soil. This set of ideas is known as the Variable Source Area Concept for that reason, and knowledge of the variation is vital to an understanding of non-linearity in catchment input-output relations. Many authors have pointed to the fact that channel lengths are variable rather than fixed in length as the method of their portrayal on maps tends to suggest (e.g. Kennedy, 1978; Day, 1978). There are some encouraging indications that this variation can be predicted, possibly from topography alone, since one detailed study in particular found that 'the network tended to expand and contract along the same routes so that for a given discharge a particular network structure could be assumed' (Gurnell, 1978,297).

Soil depth is an important control on saturation, but is difficult to measure. Betson and Marius (1969) gave an interesting example for a catchment in North Carolina, of an attempt to predict catchment

runoff from observation of a small sub-plot in that catchment, which was unsuccessful because sub-plot runoff tended to underestimate catchment runoff disproportionately. The reason for this, they found, was that the sub-plot had deep soils which absorbed and held infiltrating rainwater, and it was the areas of shallower soils particularly higher up in the catchment that were transmitting runoff to the outlet. In this instance, topography was acting as a controlling influence on runoff via the intermediary of soil depth : it would be encouraging for hillslope hydrological studies if such a phenomenon were widespread, because a variable that is difficult to measure (soil depth) could be estimated from one that is easier to measure (topography).

The importance of topography to a hydrological study also depends to an extent on the scale of that study. Hewlett and Hibbert (1967) argued that in a catchment larger than about 50 km^2 in area, travel time and storage in the stream channel - that is, runoff routing considerations - start to dominate the hydrograph such that the exact form of hillslope hydrograph response becomes of secondary importance. Most study catchments monitored to promote detailed understanding of runoff processes are smaller than this, but several hydrological models have necessarily been formulated for much larger basins, and have often thereby been able to achieve acceptable results without faithfulness to the physical reality of expanding source areas. The classes of hydrological model are the subject of the next sub-section. Arnett sums up the influence of scale in the following quotation from his study of factors controlling denudation rates : 'attention can be focussed on particular factors by altering the scale of the study. Thus the influence of lithology and landuse are established at the inter-basin level, through

slope and drainage density at the intra-basin scale down to an infinite combination of topographical, pedological and landuse components at the micro-scale' (1979,145).

1.5 Hydrological modelling

A brief outline of modelling strategies and some opinions of modellers are provided in this sub-section to indicate the range of hydrological models for which topographic data of the sort provided by this study might be required, the topographic inputs used by models to date, and perceived future priorities in the modelling process.

Hydrological models are grouped into various categories : one of the most fundamental distinctions is that between 'black box' and process models. The former 'fits inputs to outputs through a structure which may be wholly statistical or partly mathematical'; while the latter type 'purports to simulate hydrological processes on a catchment, usually by conceptualizing the catchment as a number of interconnected storages' (Chapman, 1975, 461). The disadvantage of black box models is that they cannot apply outside the range of catchments and hydrological events for which their parameters have been determined.

In practice there exists a gradation of models between the two end-members defined by Chapman : many hydrological models whose conception is grounded in such physical mechanisms as infiltration and storage, nevertheless optimize the fit between the model parameters relating to these physical processes and the runoff data to hand, because of the large amount of computational time and input data needed to depict the real world situation. The Stanford Watershed Model IV (Crawford and Linsley, 1966) is an example of a model which incorporates an optimizing routine for these parameters. Chapman (op.cit.) argued that an aim in hydrological modelling should be to define physically-

reasonable ranges for model parameters, so that if optimization routines indicated that a value of a parameter was required that was outside the latter's stipulated range, the modeller would know that his model was seriously wrong.

A related distinction is that between deterministic and stochastic hydrological models. In a completely deterministic model, all variables are regarded as free from random variation, so that none is considered to have a probability distribution. Again the majority of hydrological models lie between the two extremes, because although the runoff process is in principle deterministic, in practice it is characterized by so much variation on a detailed scale that elements of it are best modelled stochastically. This was made clear in the previous section, for example in relation to the very complex nature of flow in soils. Many hydrological modellers would probably agree with Clarke that 'the specification of $f^*(.)$ is the function of the determinist, whilst the specification of the assumptions about ε_t is that of the stochasticist. Stochastic and deterministic methods are then seen as complementary, rather than as alternatives' (1973, 8).

Another important conceptual divide is between lumped and distributed models; in the former case, 'rainfall and evapotranspiration and the model parameters are averaged over the whole catchment', whereas in the latter case 'the catchment is divided up into a number of smaller areas, each with its own representative data inputs and parameters' (Brown, 1975, 435). In practice models exist that allow for varying detail of catchment subdivision, depending on the scale of drainage basin for which the model was designed. The Stanford Watershed Model allows for division of a catchment into a number of sub-catchments, but in none of the examples given by Crawford and Linsley (op.cit.) was a subcatchment smaller than 1 km^2 employed, and in the majority of these

examples subcatchments much larger than this were used. Many studies have been concerned with spatial variation of process within catchments whose total area is less than this.

Given the range of model structures fitted to different sizes of catchment, it is evident that different kinds of topographic detail will be required by the various types. A more lumped model may benefit from incorporation of some summary statistics of stream and slope gradients and lengths, while models that split a basin up into a large number of small subcatchments would benefit from computer definition of contour orthogonals. Models that work with a regular mesh of finite differences, where 'differential equations that provide an exact, theoretical representation are approximated over finite intervals of space' (Harbaugh and Bonham-Carter, 1970, 523), are ideally suited to land form data from matrices. Examples of the types of hydrological models will be given below.

An example of a lumped model is the Natural Environment Research Council's (1975) Best Estimate of Mean Annual Flood ('BESMAF') from catchment characteristics for ungauged catchments (having no runoff records). This employed a stream slope ('S1085') variable as its only topographic input, defined as the slope between the 10 and 85 percentiles of mainstream map length (upstream from the outlet of interest). Catchments studied in this project ranged from 9868 km^2 to 0.038 km^2 (Sutcliffe, 1978, 37) in size and clearly for the top end of this range, detailed measurements of slope profiles and manual construction of matrices from maps would not be economically feasible. Yet complete coverage of Great Britain exists for altitude matrices interpolated from contours digitized at 1:250,000 scale, and from that an indication of mean and standard deviation of catchment gradient - for example - could be obtained to supplement the simple channel slope variable. It is

desirable to measure hillslopes as well as the channel slope at their foot, as gradients of the two are not necessarily highly correlated, for several reasons including the fact that 'streams can adjust their cross-sections as well as gradients to maximize sediment transport capacity' (Richards, 1982, 31). Newson in his review of the Flood Studies Report states that 'There is no doubt ... that archives of digital data from maps will, if available, be an enormous advantage to both the scope and speed of future flood studies' (1978, 280).

The Mean Annual Flood obtained from catchment characteristics was generally found to be only slightly more precise than that computed from 12-13 months of runoff record (NERC, 1975, vol 1 section 4.3.10). Newson attributes some of this lack of success to the lack of stratification (besides some regionalization) in the large sample of British basins studied in the Report. In attempting to fit one predictive equation to such a diverse set of catchments, the result was bound to be the lowest common denominator to them all, fitting none of them perfectly. Stratification by basin size merits more consideration, as perhaps would the separation of a sub-set of mountain catchments, where 'physiographic aggravation' (Newson, 1981) by steep channels and slopes promotes high runoff peaks from short, often convective, summer rainstorms.

Mention must be made of attempts to explain residuals from BESMAF in terms of topographic attributes including profile and plan curvature, using a matrix approach similar to that used by program G (Beran, 1981; Heerdegen and Beran, 1982). The authors had little success, and suggest that this was because of 'the generalisation of slope form which has to be undertaken to produce the parameters'. They used matrices with mesh sizes ranging from 23.5 to 100 m on small catchments (several were less than 15 km^2 in area), and since curvature measurements from matrices are very sensitive to the scale of measurement (as is shown by much evidence

presented later in this thesis), Heerdegen and Beran's finding should not deter hydrologists from further investigation of the predictive value of curvature.

Anderson (1973) reported an interesting attempt to use six parameters derived from overall drainage basin morphology in a model of catchment runoff variation. In the example presented in detail in the paper, the shape of an 11.4 km^2 catchment was approximated by a leminiscate loop : a highly flexible shape defined when only the area and length of the basin concerned are known. Thirty heights were determined at points around the catchment's watershed and to these was fitted a second degree polynomial, its three coefficients providing the third, fourth and fifth parameters in the model. The sixth was the gradient of the main stream. Anderson claimed some success in modelling 'short term changes in flow'. The importance of this study lies in its use of a type of model of drainage basin terrain, rather than some average slope value as is common practice in lumped parameter hydrological models. Unfortunately few other studies have used such an approach.

The profile and matrix method of this thesis is more appropriate to the scale of catchment to which Topmodel, a 'physically based, variable contributing area model of basin hydrology' (Beven and Kirkby, 1979) has been applied, for instance to Crimple Beck in Yorkshire at 8 km^2, than to the larger catchments included in the NERC (1975) Report. At present Topmodel's topographic input consists of the natural logarithm of area drained per unit contour length divided by the tangent of local slope angle - i.e. $\ln(a/\tan\beta)$ - which must be estimated for a number of subjectively chosen subdivisions of the catchment. More recently Beven and Wood (1983) have suggested subdividing a catchment into a number of 'idealized flow planes' for which distributions of the required topographic parameters could be derived analytically. There is also

scope for improvement in topographic input for this model derived empirically from a regular net of measurements of altitude, gradient, aspect, plan and profile curvature for every grid point of a matrix covering the area (output by program G as described in section 1.3). If more detail was required, a few slope profiles could be measured in the field, selected to give areally reliable results in a way to be outlined in this thesis.

Profiles constructed quickly from matrices by SLOPROFIL. 2,the program especially written for this research, could be used to draw the boundaries of subcatchments. Contour orthogonals are the natural course of such boundaries because of the general premise that mass and energy flow down rather than across them. Boundaries of this sort are a requirement of Topmodel, and also of a finite element model presented in a paper by Jayawardena and White (1979) in which are reproduced striking maps of the Wye and Severn catchments divided into thin strips of land orthogonal to contours. The model determines outflow volumes for each strip.

An example of a finite difference model is SHE (Système Hydrologique Européen)(Beven and O'Connell, 1982), which uses a grid square basis for its topographic input. However only mean altitude and surface slope are calculated for each grid square. No mention is made of curvature either in profile or in plan, in an otherwise sophisticated and explicitly physically-based model.

The choice of a lumped or distributed model depends to a great extent on the purpose of a study; in view of the demonstrated variability of hydrological response for example between headwater and sideslope areas, it is inevitable that distributed models will be more physically-based, and therefore stand a greater chance of advancing our understanding of catchment hydrology. This latter is an aim in

geographical hydrology, while speed and economy may dictate the use of black box and lumped models by practitioners : for example Lowing and Reed state that 'Data requirements for this physical approach generally restrict it to research use' (1981, 52). Geographical hydrology should not detach itself from the requirements of practical specialists however : the tendency to study processes in more and more detail at very narrow spatial scales does not necessarily advance our understanding of flow generation at the catchment scale. Meanwhile practitioners continue in ignorance of any advances in understanding that have been made at scales not of interest to them. Hence the focus in this research is always on efficient methods of measuring topographic form, and on identifying features detectable with different resolutions of measurement, the implication being that the hydrologist is free to make an informed choice of the appropriate scale of measurement for his model.

There are a few interesting references in the literature to the sort of scales of topographic information appropriate for hydrological modelling. Anderson and Burt justified their use of a 10 m sampling grid of altitudes rather than more detailed measurements of topography advocated by Speight (1980), because 'the overall pattern of soil water is related to the broad form of the entire hollow rather than to local variations within it' (Anderson and Burt, 1980, 193). Bernier (1982) attributed some lack of success in runoff prediction for a 24 hectare catchment with USAS2, a 'revised source area simulator for small forested basins' to the model's crude characterization of topography and soil depth, such that small irregularities leading to local saturation before and after widespread saturation in an area were not picked up. A hollow draining an area of interfluve at Eastergrounds in Slapton Wood Catchment, South Devon, has been monitored by workers at Huddersfield Polytechnic and a report appears in a paper by Burt et al (1983).

They argued that such hollows, of about 200 m^2 area, act as foci for water draining down from the interfluves to the main stream, and as such must be included in catchment models.

In view of the variety and sophistication of existing hydrological models, several workers argue that research effort should not be devoted to further model-building (e.g. Chapman and Dunin, 1975) but to 'measurement or rational estimation of appropriate physical characteristics of the catchment, the so-called catchment parameters. The two major constraints on significant advances will then be the acquisition of the appropriate data at reasonable cost, and the complexity of implementing the more realistic models; the problems are technical (and indeed partly economic), rather than conceptual' (Chapman, op.cit., 459). While this thesis concentrates on topography, it is recognized that advances will need to be made in the quantification of the other hydrologically relevant variables that vary in space before models can benefit fully from this more detailed spatial array of land form information. Of particular importance is the estimation of rainfall variability over a catchment : Crawford and Linsley (op.cit.) identify this as the single most critical factor in successful simulations using the Stanford Watershed Model, and recommend a minimum of two recording raingauges per catchment however small the latter may be. The recognition that soil permeability varies laterally due to the presence and importance of macropores in a wide variety of environments (e.g. Beven and Germann, 1982) has highlighted the need for more research into subsurface runoff rates also.

1.6 Structure of thesis

In chapter 2 the two British drainage basins, Gara and Netherhearth, studied in depth in this research are introduced, and the implementation of slope profile surveys in them by traditional means is described. Field

survey is needed to establish the quality of matrix-derived land form data. The subjectivities and difficulties with the traditional method also need to be made clear before work on the computer is brought to bear in trying to resolve them, later in the thesis. Particular emphasis is placed on the implementation of different patterns of profile sampling, a recurrent theme in the research.

In chapter 3 construction of altitude matrices of the two areas is outlined, incorporating a comparison of manual and semi-automated methods possible using the sort of equipment available to all geomorphologists competent on computers. Some results from processing the matrices with program G are then presented in an investigation of the sensitivity of land form attribute values to the resolution (grid mesh) of matrix data.

In chapter 4 matrix and profiling methods are combined for the first time, at least in theory, in explaining the construction of the program SLOPROFIL.2 to draw profiles through matrix information. Since this program is fundamental to what follows, it occupies chapter 4 rather than being relegated to an appendix (where a listing of the program does appear). In chapter 5 profiles produced on computer are compared with the same profiles measured in the field, to test the validity of profiling with SLOPROFIL.2. Since the comparison involves a contrast in scale and in source of data (map versus field), various tests are carried out to isolate the separate contributions of these influences.

In chapter 6 the method of determining correct profile terminating conditions for SLOPROFIL.2 to achieve representative areal coverage by profiles as judged by comparison with results from G, is exemplified for the field-surveyed profile pattern in the Gara, forming an introduction to the issues involved in this process of profile calibration. Then very large profile samples are generated on computer for that catchment, taking

advantage of the incomparably greater speed of profile generation using SLOPROFIL.2 than by fieldwork, to investigate the visual completeness of surface coverage attainable by profiles traced from various patterns of points of origin. In chapter 7 the statistical comparability between G results and those from computer profile samples of various sizes in Gara and Netherhearth catchments is investigated in the context of the map coverage demonstrated in chapter 6. Sample sizes, terminating conditions and profile patterns for the two catchments are recommended.

In chapter 8 there is a detailed investigation into the effects of scale (of matrix grid mesh and profile steplength) on the profile paths and summary statistics obtained from computer profile samples. This leads into an investigation of differences between results from SLOPROFIL.2 and G, consequent on the different ways that they model a surface : the former as continuous and smooth, while the latter only samples at one point per local surface, so that this need not have a smooth junction with the next surface.

In chapter 9 the procedure of fixing appropriate profile sampling design, sample size and terminating conditions is carried out on a new and unvisited catchment to investigate how easily applicable the method is, and how widely applicable the conclusions already drawn from study of the other two catchments. This new catchment is that of the Ferro, for which a matrix already existed (as described in Evans, 1979). Finally in chapter 10 conclusions are presented from the study and applications in the hydrological realm are suggested.

1.7 Notation[1]

a area drained per unit contour length

β local slope angle

ε_t error terms in an equation

$f^*(\cdot)$ deterministic function in an equation

X one of two perpendicular coordinate directions in the horizontal plane; increases from West to East

Y one of two perpendicular coordinate directions in the horizontal plane; increases from North to South

Z vertical coordinate direction signifying altitude, in plane at right angles to the horizontal plane

[1] For ease of reference, each chapter has its own notation list. Every effort has been made to be consistent between chapters, but some clashes were unavoidable due to conflicting established uses of some characters, such as 'n'.

CHAPTER 2 : STUDY AREAS AND FIELD PROFILE SURVEY

2.1 Introduction

2.2 Choice of study areas

2.3 The Gara catchment : topography and drainage

2.4 Slope profile survey : some definition of method

2.5 The siting of profile points of origin : introductory remarks

2.6 Grid scheme

2.7 Profile sampling baseline scheme

- 2.7 i General remarks
- 2.7 ii Preparation of basemap and issues raised by it
- 2.7 iii Construction of PSBL on basemap

2.8 Alignment and survey of profiles in the field

- 2.8 i General considerations
- 2.8 ii Termination
- 2.8 iii Obstructions

2.9 Comments on survey according to the two sampling schemes

- 2.9 i Grid scheme
- 2.9 ii PSBL scheme

2.10 Conclusions on profile survey in the Gara

2.11 Plan curvature

2.12 Netherhearth Sike catchment : topography and drainage

2.13 Measurement of selected slope profiles in Netherhearth catchment

2.14 The issue of similarity between adjacent profiles : comparing Gara and Netherhearth

2.15 Conclusions on slope profile survey in the field

2.16 Notation

2.1 Introduction

In this chapter the selection of slope profiles according to two main types of sampling scheme is described, together with their survey in the field using simple instruments as is usual for this morphometric method. Field survey is necessary at this point because of the oft-stated belief among geomorphologists that 'valley-side profiles (unlike longitudinal stream profiles) cannot be at all satisfactorily obtained from even the most accurate contour maps in common use' (Chorley, 1964, 70). This type of statement will be open to qualification in the light of results from computer-generated slope profiles using altitude matrix data obtained from maps, in later chapters. The field profiles are needed however to verify the computer work.

It was hoped that data from the field survey would reproduce as closely as possible characteristics of the frequency distributions of altitude, gradient, aspect, and profile and plan convexity (justified in chapter 1) for the land surface of an area as a whole. Few geomorphologists who have written about profile survey have expressed the aim of sampling land surface attributes and consequently there is little directly relevant experience to draw on in this study. In this chapter particular emphasis is therefore placed on explicit statements of how choices were made at points where existing advice is vague or seems to make assumptions about the sort of topography under study that were not found to be valid in the areas chosen here. Fieldwork was undertaken in two British drainage basins whose selection is explained in the next section.

It was recognized that the resulting profiles could fall short of the aim of areal representativeness, partly because of the lack of knowledge as to the exact means of achieving this aim. In that case the usefulness of the survey would also lie in exposing some of the

problems with the technique as a way of sampling a land surface. Data from matrices will be used in later chapters to recommend sampling design, sample size, and decisions over profile termination,for field profile survey - all issues which receive attention in this chapter. All profile surveys make compromises, the most common of which are discussed in this chapter : this research sets out to recommend efficient ways of survey by demonstrating the consequences of choices to be made.

2.2 Choice of study areas

The two catchments chosen had to satisfy the following conditions:

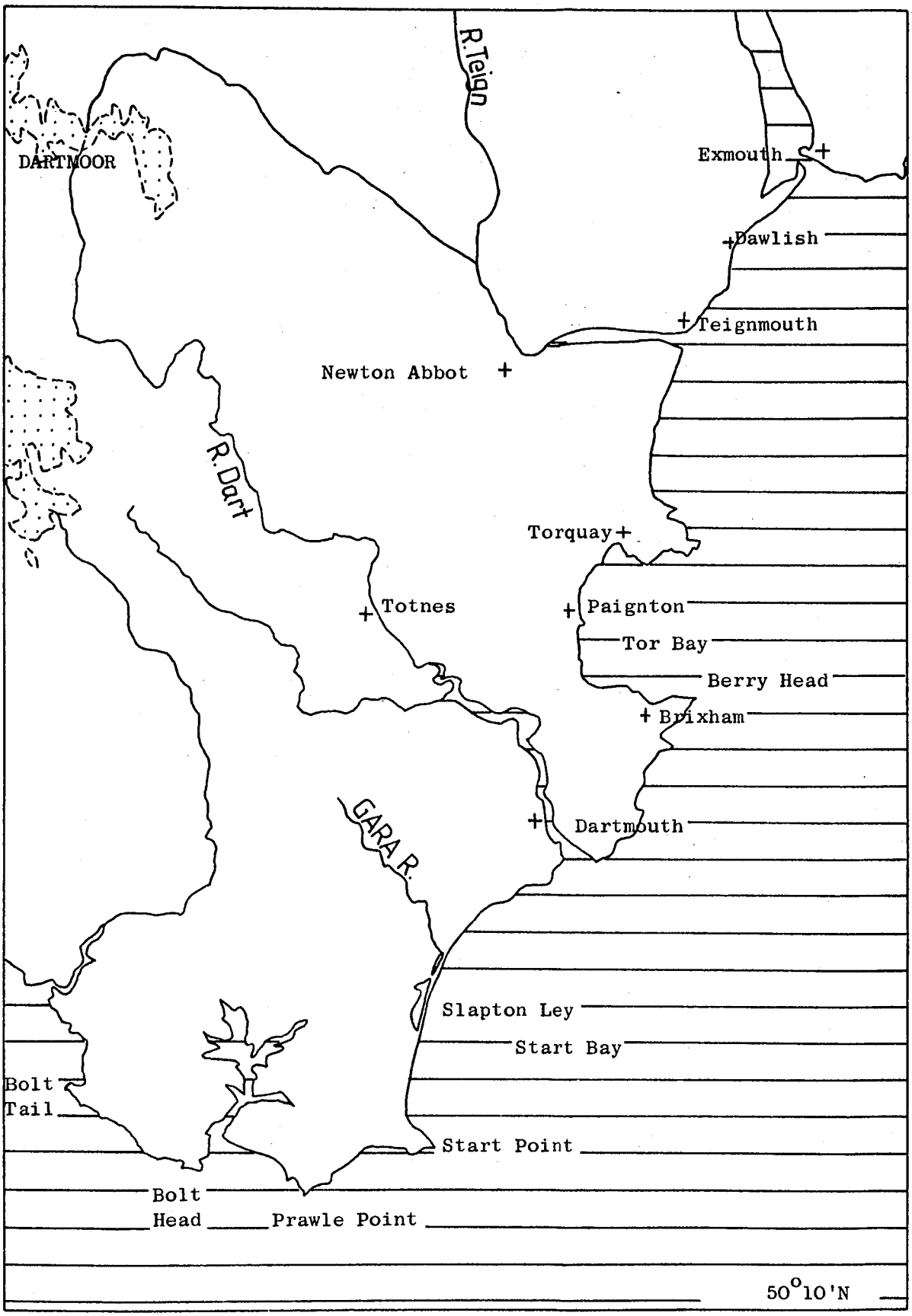
1. areas must be small enough to enable a matrix to be made at as detailed a scale as the available map data would justify, within a reasonable amount of time;

2. land must be accessible for a field measurement programme;

3. the two catchments must have contrasting topographies so that the methods being tested would come up against some of the range of land surface types to be found in this country;

4. the two catchments should represent types of topography commonly found in Britain, rather than unique occurrences, so that conclusions drawn from them are likely to have wide applicability.

The two basins chosen were the Gara River catchment in South Devon, having an area of approximately 27 km^2 (Van Vlymen, 1979), whose location is shown in figure 2.1;and Netherhearth Sike catchment, occupying 1.3 km^2 and tributary to Trout Beck at Moor House in Upper Teesdale, as shown in figure 2.2. The Gara catchment is mostly agricultural land, but all the farmers know of the Field Studies Council's Centre at Slapton near the mouth of the basin, so that this could be mentioned in conversation to them as grounds for gaining access to their land. Netherhearth Sike's catchment is the property of the Nature



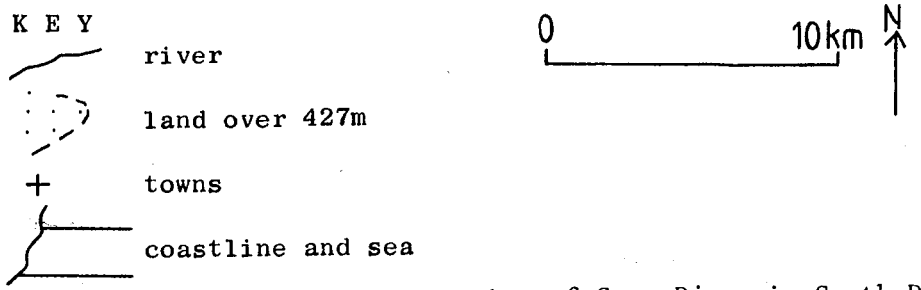


Figure 2.1 : Map showing location of Gara River in South Devon, England.

Figure 2.2 : Map showing location of Netherhearth Sike in Northern England.

Conservancy Council at Moor House, and access to it was granted by the Officer-in-Charge, Mr. M. Rawes.

The Gara catchment is covered by non-photogrammetric 1:10,560 scale Ordnance Survey maps. A major factor behind the choice of Netherhearth Sike's catchment as a study area was the availability of a photogrammetrically-derived 1:2,500 scale map of the area constructed by Mr. M. Evans of Newcastle Surveying Department; from this it was possible to make a detailed altitude matrix, as will be described in chapter 3. Thus the study of the two catchments incorporated a contrast in scale, an issue already identified in chapter 1 as lying at the core of this research.

The two catchments also present interesting topographic contrasts for morphometric study. Netherhearth Sike is a small tributary stream, for much of its length barely incised into the long valleyside of Trout Beck, a fairly typical upland moorland catchment. The topography of the Gara catchment accords more fully with the degree of dissection by drainage that tends to be taken for granted in literature on profile sampling strategy than does the Netherhearth catchment. Most profile survey has been concerned with 'mature' drainage basins in the sense defined by Melton of 'a basin whose every channel has developed a watershed with smooth slopes extending to the divides ....In spite of past discreditable associations, "mature" can be used safely as a strictly descriptive term' (1958, 36).

The Gara's topography is not classically 'mature', in that summits are rounded and of low gradient, rather than sharply-defined. This is a common situation in Britain however, as is attested by the popularity of denudation chronology at one time in geomorphology. Poorly-dissected peat catchments like the Netherhearth are very common in British upland moorlands, and receive much attention in the hydrological literature

partly because they form the source areas of rivers important to large populations, exerting a strong influence on the hydrology of those rivers.

The greater dissection of the Gara catchment meant that it was more suited to testing existing profile sampling strategies. This catchment therefore forms the main focus of field survey by profiling in this study, and is described in more detail in the next section. A more limited survey was carried out on the Netherhearth at Moor House, and will be outlined in sections 2.12 to 2.13.

2.3 The Gara catchment : topography and drainage

The basin's 27 km^2 encompasses a maximum altitude of 216 m OD at Stanborough Camp on its north-western edge, and a minimum of 3 m at its marshy outlet into Slapton Ley, making for an altitude range of 213 m. 'Topographically, the catchment is dominated by the gently sloping ground ($< 5°$) above the 90 m contour which affords excellent mixed farming. This contour generally coincides with a marked break in slope and below it the valley sides are much steeper (up to 25°)' (Burt et al, 1983, 732). These topographic contrasts can be seen in figure 2.3. Towards the outlet of the basin, valleyside slopes are generally steepest and are frequently wooded; the Gara's floodplain is also more developed here and makes for a sharp change in gradient from the valley sides.

The land surface and drainage system are well integrated in the sense that most tributaries marked with a blue line on the 1:25,000 scale Second Series Ordnance Survey maps flow in well-defined valleys. Towards its outlet the Gara meanders across an ill-drained area, eventually traversing a reed swamp before entering Slapton Ley. The impression of good drainage in some of the valleys higher up in the catchment may however owe much to man's intervention, as is explained in section 2.7.ii.

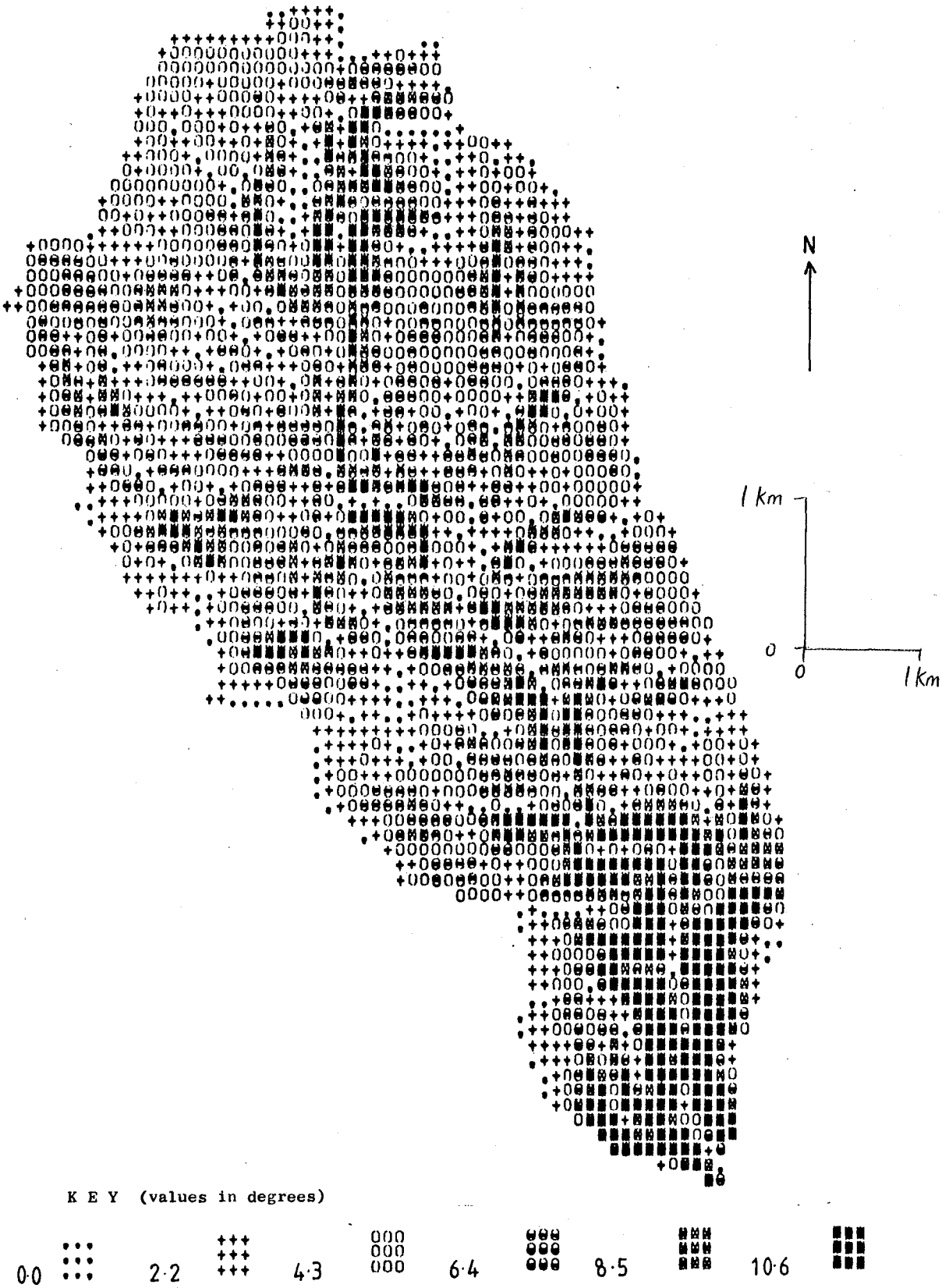


Figure 2.3 : Map of gradient from Gara matrix at 100 m mesh.

The catchment is underlain by Devonian slates and grits (Orme, 1960) with superficial deposits of soliflucted 'head' material infilling valley bottoms and valley head depressions to a depth of 5 m or more (Burt et al, op.cit). Land use is predominantly agricultural, with the exception of the wooded and waterlogged areas mentioned.

2.4 Slope profile survey : some definition of method

The British Geomorphological Research Group (hereafter BGRG) Technical Bulletin on slope profile survey (Young, 1974), already referred to in chapter 1 section 2, represents a valuable attempt to standardize the execution of this technique; it will be much quoted from and critically examined below. A slope profile is a line along the ground surface largely following the direction of 'true slope', that is following the maximum surface slope angle of the ground, in effect perpendicular to contours. There are two stages in determining the location of a profile line : the siting of a point of origin, which is often carried out on maps or air photographs; and the alignment of the profile up and downslope along a true slope path from the point of origin, which must always be done in the field. The first stage is discussed for the Gara in sections 2.5, 2.6 and 2.7; the second forms the subject of the Gara field survey in sections 2.8 and 2.9.

Thus in the field one attempts to locate accurately the point of origin already chosen and marked on a map of the area for example, and then the survey proceeds by taking a series of pairs of measurements of angle (read here to the nearest $\frac{1}{2}°$ with hand-held Suunto clinometer) and distance along the contour-orthogonal path passing through the point of origin, continuing until both crest and talweg have been surveyed. It is recommended that angle measurements be made over an unvarying ground surface length of 5 m as was done here, given the demonstrated

dependence of results obtained on the distance over which gradient is measured (Gerrard and Robinson, 1971). Pitty puts forward another good argument for the use of constant ground surface lengths, in that otherwise the method would depend 'on the measurement of two quantities, the angle of declivity and the extent of the measured length, whereas an observation is commonly a scalar, not a vector quantity' (1967, 67).

In practice Young (1974) sanctions some relaxation of the condition of orthogonality to contours in profiling. Where divides are plunging or where near a river channel the talweg may be following a steeper course than the gradient of the lowest portion of its flanking valley-sides, a profile following true slope at all times should strictly approach divide or talweg asymptotically. Young recommends instead continuation of the path established on the bulk of the hillslope. Since talwegs rarely slope at angles larger than 1°, most geomorphologists are content to continue a profile along its established path to the stream or centre of the valley floor. However more controversy surrounds the case of divides plunging at gradients greater than 1°, where Young's 'perpendicular extension procedure' (ibid, 23) may involve the geomorphologist in taking a considerable number of measurements which are not of true slope, before the crest is passed. Pitty (1966) suggests termination of a profile where the slope perpendicular to it becomes greater than that of the profile line at that point and Gerrard (1982) for example follows suit. Young argues that this 'cut-off procedure' will leave crestal areas unsampled.

In this study the aim was to follow true slope at all times so that measurements could be generated to compare with true-slope output from calculations on altitude matrix data, and because interest in hydrology focusses on the path that water would take down a hillside. However this study was not restricted to measurement of only those

(true) slopes that could be followed along a constant bearing as Pitty also advocates, because of the desire to measure all slopes, including those not 'relatively straight in plan', for reasons stated in chapter 1. It was therefore often a problem to decide how much deviation of bearing would justify profile termination, an issue that will be dealt with in the light of examples from the field survey in section 2.8.ii.

Slope profile survey also requires other choices, to be discussed where they arise in the following outline of the method as it was applied in the Gara catchment.

2.5 The siting of profile points of origin : introductory remarks

The best way to choose a sample of slope profiles for survey from the infinite number of such lines which exist in any dissected landscape is, not surprisingly, an unresolved issue in geomorphology. The consensus is that the worker should choose a sample of points in the landscape and extend profiles from them in the field, but the choice of a pattern of points so as to give an even coverage of lines is not a simple matter, as is stressed in the statement by Cox quoted in chapter 1 section 2.

The study in the Gara catchment employed two contrasting schemes of twenty profiles each, to evaluate their relative merits; these schemes were based on a grid pattern of points, and on the profile sampling baseline recommended by Young (1972, 145-6; 1974, 17-18). This thesis is concerned with evaluation of sampling schemes for their ability to reach all slopes in a catchment without over-representing any one area; subsequent stratification of points of origin for the purpose of survey - for example by valley order, as implemented by Arnett (1971) - is not of primary concern here. This is because it is safe for a geomorphologist to take a stratified sample of points of origin only when he is satisfied that the whole population of these points would not give

a biased sample of the landscape. The stratification itself is a secondary concern, not pursued in this research.

A total of forty profiles were chosen for survey in accordance with Blong's (1972) identification of the average size of sample in profile surveys; it must be recognized however that the ensuing density of coverage of the catchment by profiles (see sections 2.6 and 2.7i below) was well below that of some workers such as Parsons (1979) who used 200 m spacing along the profile sampling baseline he established in East Sussex valleys. The theme of sampling density will be discussed in section 2.14,and will recur in later chapters.

2.6 Grid scheme

While there are few objections to the sampling of land height by a grid pattern of spot heights, the quality of coverage yielded by profiles drawn from grid points is more contentious. A.Young (1974) maintains that profile lines drawn from a grid (systematic) or random pattern of points (both 'surface-random' in that point spacing is not conditional upon any properties of the land surface in question) will under-represent convexities low down in the landscape ('noses') and over-represent concavities there. This is because lines of true slope diverge downslope over plan-convex areas, and converge downslope on plan-concave areas; the reverse is true for lines climbing towards higher ground.

On the other hand, the generation of a grid pattern of points guarantees even areal coverage of points of origin and is simple, involving none of the subjectivity required in the construction of the profile sampling baseline described in section 2.7 below, so the survey included a grid sample in order that comparisons could be made with the more popular 'surface-specific' method.

A sampling grid mesh of 1.15 km horizontal distance on the ground was chosen, since exactly twenty profile points of origin could be generated in the Gara catchment using that spacing.

2.7 Profile sampling baseline scheme

i. General remarks

This line (hereafter the PSBL), conceived and named by A.Young, is to be constructed half way between divide and talweg for all valley-sides, forming a locus for profile points of origin. Young claims that the PSBL will minimize bias associated with a random or grid pattern of points mentioned in section 2.6, bias that would be most marked if divides or talwegs alone were used to define points of origin - although he does not consider using a combination of divide and talweg points of origin (explored in this thesis using matrix data in a later chapter). Young gives little further advice as to how to construct the PSBL.

In the Gara catchment study it was felt necessary to implement the PSBL scheme as it represents the BGRG's recommendation on profile sampling, and has been used by other geomorphologists (such as Parsons, 1979, 1982) who express an interest in estimating the properties of a surface by profiling. The PSBL constructed for the Gara was digitized with a line-following cursor on a Summagraphics digitizing table, and a small FORTRAN program was written to locate twenty points of origin at equal intervals along it : spacing worked out at 3.67 km measured along the PSBL.

It is necessary here to detail the construction of the PSBL before discussing the work in the field, since it would seem that there is much room for operator variance in interpreting Young's guidelines on this procedure.

2.7ii Preparation of basemap and issues raised by it

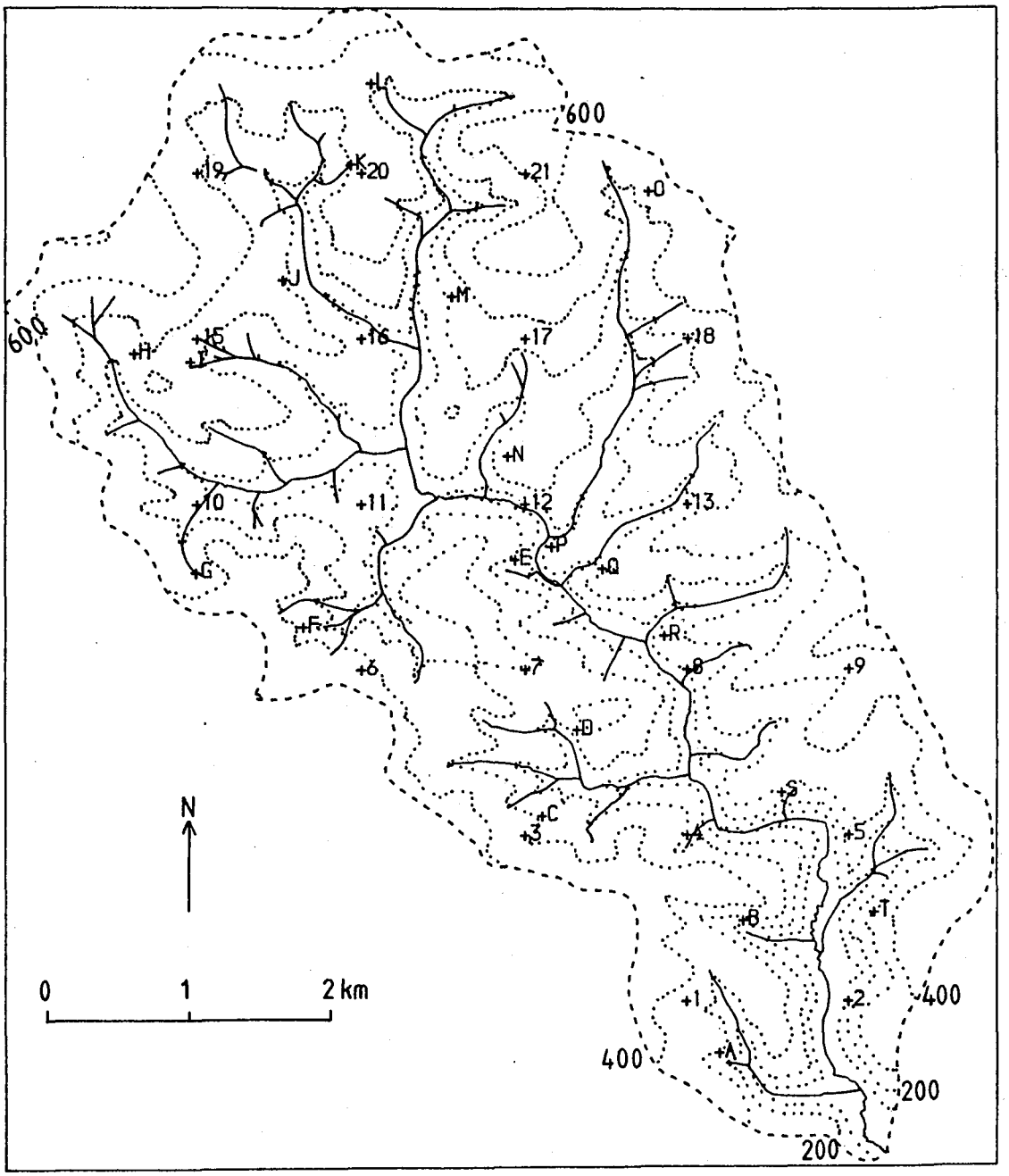
To avoid the confusion of trying to mark divides on a printed Ordnance Survey map, contours at 100 foot intervals from the 1:10,560 map together with the blue line stream network as depicted with greater clarity (and the same amount of detail, according to Gardiner, 1971) on the 1:25,000 Second Series maps were digitized on the Summagraphics table and plotted at a scale of approximately 1:20,000 (or exactly 1 inch to 500 m). Divides were then drawn around the valleys defined by all streams - excepting the very smallest fingertip tributaries (less than about 60 m long), using the digitized contour information and referring back to the OS map. Some arbitrariness was involved in deciding on the positions of divides on gently sloping hilltop areas, a situation by no means unique to this study area as the following quotation from Werner illustrates: 'The identification of the precise location of ridges becomes, at times,impossible, especially when erosional processes have either not sufficiently advanced so as to reduce remnants of plateau-like forms to a pattern of well-defined slopes and crests or, for reasons of climate and geology, will never produce a sharply defined dissection' (1982,1001). He recommends 'a consistent application of explicit rules'. Two guidelines were especially useful here : one, that a watershed should always cross a contour at right-angles to it; and the second, that lower-order catchments form a space-filling series and should not therefore have outlines rounded off to conform with popular conception of drainage basin shape (Gardiner, 1975).

Another cause for concern was the apparently arbitrary nature of some of the blue line network. This representation of the river system was chosen following closely the recommendations of the BGRG Technical Bulletin on drainage basin morphometry (ibid) in settling upon a reproducible standard for geomorphological studies. Some marked contour

concavities (or crenulations) had no blue lines associated with them, as was the case near the location of the point of origin of profile 1 for example (figure 2.4), while other blue lines marked on the OS map were associated with minimal deviation of contours - for example at the site of profiles I and 15. During fieldwork involving much conversation with farmers over the request to survey on their land, it became clear that a great deal of artificial land drainage has been undertaken in the catchment. In one extreme case a valley system marked as containing blue lines on the OS map, at the site of profiles K and 20, appeared as a set of completely vegetated dry valleys in July 1982 due to man-made diversion of the streams underground.

In retrospect it seems that it would have been less arbitrary (although more time-consuming) in practice to define talwegs in terms of contour crenulation of some threshold size. As far as survey in the field itself was concerned, profiles were terminated at a significant local base level as Leopold and Dunne (1971) suggest, where downvalley processes take over from downslope ones, whether or not such a talweg had a blue line marked in it on the map. However, as regards the PSBL, the damage had been done by the time fieldwork started : if an artificially-drained valley had not been marked with a blue line on the map, the PSBL was not deflected around that valley, and so there was less likelihood of a profile point of origin falling in it.

Young does not define the term 'talweg' except via a rather circular argument : 'A talweg ... is a line passing through the base of a profile and separating slopes of approximately opposite aspects which are inclined toward each other; it is frequently, but not necessarily, a stream channel' (1974,6). This does not give any guidance as to what should happen at the valley head, and Young himself seems indecisive over this situation, implying in his 1974 diagram (page 18) that one is



K E Y

+1 position of point of origin (labelling numeric for grid scheme, alphabetic for PSBL scheme)

200 ..... contours (heights in feet)

stream network

catchment watershed

Figure 2.4 : Map showing locations of points of origin for profile survey in the Gara catchment.

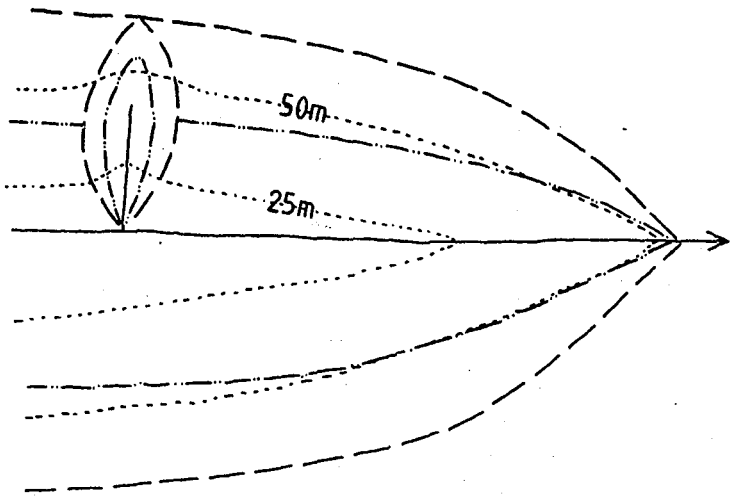
sometimes justified in extending first-order talwegs to the divide, yet omitting this suggestion from the otherwise similar diagram in his earlier book (1972, 145). On neither diagram does he show any contour information to help the reader to see the logic of his decision on some quantitative grounds.

In view of the greater difficulty in deciding on the path of a true slope line where there is appreciable plan curvature (i.e. contour curvature), as at valley heads, many geomorphologists restrict profiling to slopes 'relatively straight in plan' where aspect changes by less than 15° over 100 m (Young, 1974, 7), in which case Young's inconsistency does not matter. Pitty (1969) adds that restriction to straight slopes in plan is a good idea on sampling grounds since it means that any one profile surveyed is likely to hold true for profiles measurable along a stretch of land either side of that profile. However if representative coverage of a land surface is desired, as here, this restriction is unacceptable : the effects of such a restriction are explored on computer later in the thesis. Rounded heads of first-order valleys are hydrologically important sites in a drainage basin also, as was explained in chapter 1.

It was never felt justifiable to extend the talweg to the divide in this fieldwork, as most valleys began as semi-circular hollows rather than retaining a v-shape right up to the watershed. The blue line network was a satisfactory guide at least on this issue.

2.7 iii Construction of PSBL on basemap

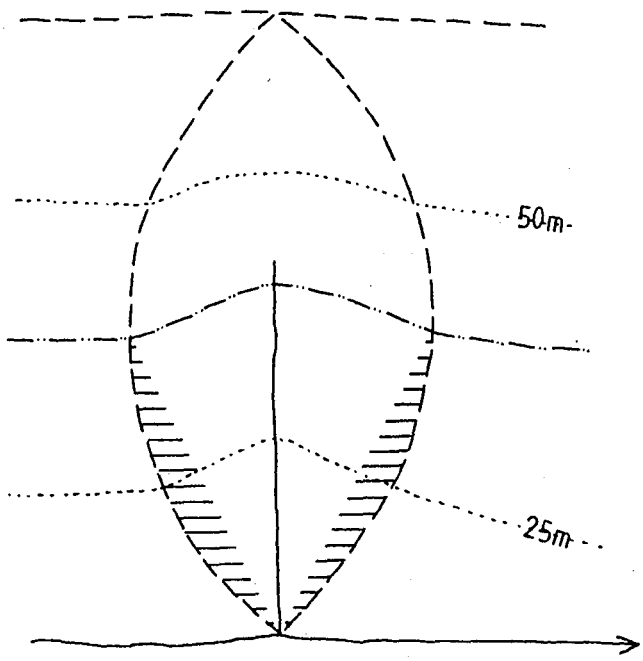
It was clear that taking a line midway between all blue lines and divides would lead to a high probability of picking a point on the PSBL corresponding to a very short slope profile, and to a greater probability of picking points in first-order valleys than their area alone would justify; a situation illustrated in figure 2.5. Therefore a scheme was



KEY

See figure 2.6

Figure 2.5 : Diagram to illustrate the large deviation of Young's PSBL around a small first-order valley.



KEY

divides

stream network

50m contours

profile sampling baseline

area of nose slope unreachable by profiles extended from new PSBL

Figure 2.6 : Diagram to illustrate the modification to Young's PSBL made in this study for small first-order valleys.

adopted in which much more notice was taken of contours in deciding the deviation of the PSBL around a stream, so that the PSBL for the hypothetical first-order valley of figure 2.5 is transformed into that depicted in figure 2.6.

A new rule had to be devised, if the PSBL in a tributary valley was not necessarily going to be taken to the confluence of the rivers, to determine how far down to draw the ends of the PSBL as depicted in figure 2.6. Small areas of 'nose' slope (shaded on that figure) were bound to be unable to be sampled with this modification; for the Gara catchment it was decided that slopes shorter than a threshold length of about 100 m could be left out rather than diverting the PSBL into a nose to get at them. This seems arbitrary but it is argued here that the alternative (figure 2.5) is less acceptable.

This discussion illustrates the delicate compromises that have to be made in the construction of a PSBL; it seems unlikely that two geomorphologists working only from Young's specifications would arrive independently at the same PSBL in a valley system like the Gara's. Young's major omission, as was mentioned earlier, is to omit contours from his illustrating diagrams; in this study it was found that the contours were a vital guide to configuration of the PSBL. This would seem to be an advantage in that contour information is probably the most reliable available for the construction of a PSBL, given the reservations about blue line and divide detailed in section 2.7 ii above. Areal coverage of profiles achievable from a large sample of PSBL points of origin was investigated by computer; the results are presented in chapter 6.

2.8 Alignment and survey of profiles in the field

i. General considerations

It is stressed in the literature (mentioned above) that although points of origin can be chosen using maps and air photographs, alignment of profiles from these points should be undertaken in the field. It is therefore of critical importance to locate a point of origin correctly in the field before the line of survey can be defined. Thus, if maps are being used (as was the case here), the fieldworker is very dependent on their accuracy, and on being able to identify reference landmarks depicted on them in the field to help to define the point to be surveyed from. In the open moorland of the Netherhearth catchment this is very difficult, as will be described in section 2.13; in the Gara catchment the situation was made much easier by the delineation of field boundaries on the OS 1:25,000 Second Series maps used in fieldwork, many of which turned out to be dense hedgerows which had obviously been present at the time of map survey and before.

In this survey very little fault could be found with the OS maps : the agreement between hedgerow in the field and field boundary marked on the map was in most cases excellent. However during the following discussion of the sensitivity of profile line defined to precise location of point of origin, it is important to bear in mind how much the ease and accuracy of locating points of origin relied on a feature not much found outside the south-west of England (hedgerows of great antiquity) and a service not parallelled in many countries outside Britain (the Ordnance Survey).

It is particularly important to locate the point of origin correctly in areas of appreciable plan curvature (converging or diverging contour-orthogonal lines), since a slight shifting of the point in a lateral direction could lead to survey of very different true slope lines,

as is illustrated in figure 2.7. Measurement was not restricted to profiles that could be surveyed along a constant bearing : thus either profile I (curved) or II (straight) in the hypothetical situation depicted in figure 2.7 could have been surveyed, depending on the location of the point of origin. Parsons (1973) justifies a restriction to slopes of constant bearing on the grounds that it would be too time-consuming to determine frequent changes in the direction of true slope. In this study the bearing was not allowed to vary between every 5 m measured length, partly for reasons of time and partly because it would have meant that every hummock in the path of the profile could disturb its orientation. Rather, since profile survey involved laying out successive 30 m lengths (tape measure fully extended) to define six 5 m lengths for angle measurement at a time, the orientation chosen was that for which the majority of the 30 m length in question was judged to be correctly following true slope. This judgement was performed by eye; sighting downslope as estimation of steepest descent is said to be most reliable when viewing from above (Young, 1974, 20).

2.8 ii Termination

When surveying slopes not straight in plan, one is already allowing the profile to change in bearing as profiling proceeds : the question is, how much of a bearing change constitutes grounds for termination? There is no guidance in the literature on this subject, as is illustrated by this quotation from Pitty : 'unless it is accepted that a slope-profile is straight in plan, as well as orthogonal to the contours, there can be no logical upper limit to a profile until the highest point in the whole area is reached' (1966, 456).

Few problems were encountered in deciding the path or termination point of a profile in its lower reaches , as slopes in the Gara tend to steepen towards the river, where survey naturally stopped, downvalley

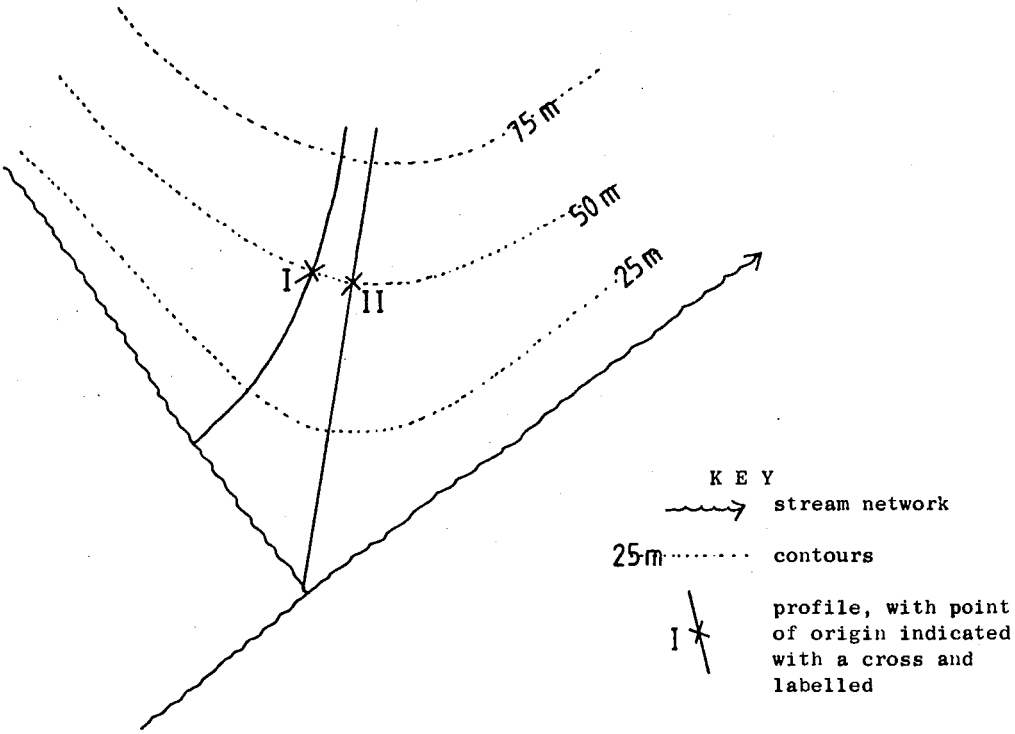


Figure 2.7 : Diagrammatic representation of the large effect on profile path that may be caused by a small displacement of the point of origin.

processes taking over from downslope. For this reason survey of profile lines was usually begun (after initial definition of the path of the profile) at the lower end, and measurement proceeded upslope until it was judged that to continue along a true slope path would involve a large bearing deviation from that followed previously. It would be arbitrary however to set precise numerical limits on the word 'large' as used here for the field survey : usually an angular change greater than 45° would provide grounds for termination, but this was always considered in the context of the path followed by the majority of the profile measurements already made, so that termination would be brought about if further profile continuation would make for a break in the continuity of a mainly straight or smoothly curving profile line.

The procedure can be illustrated best by an example from the Gara: referring to figure 2.8, profile R undergoes a total change in orientation of 47½° from its base in the talweg to its upper end running along the plunging divide; this happens in a series of steps (of 7°, 30½°, 8½° and 1½°),which in the context of a curving profile are acceptable. Profile 8 first swings through an angle of 28° to negotiate the same nose slope as R, but ends at the divide since a sharp turn through 61½° would have been required for it to run along the divide as R does. In the event, profile R was terminated shortly after the position of the crest of profile 8, since reverse slopes were encountered : this is probably common on plunging divides as water and waste will eventually find their way down flanking valleysides.

Later in this thesis, the construction of a computer program to draw slope profiles is described (chapter 4). Clearly, precise termination conditions must be formulated for this procedure : this is done by incorporating these conditions as variables in the program, whose values can be chosen by the user for optimal performance in the

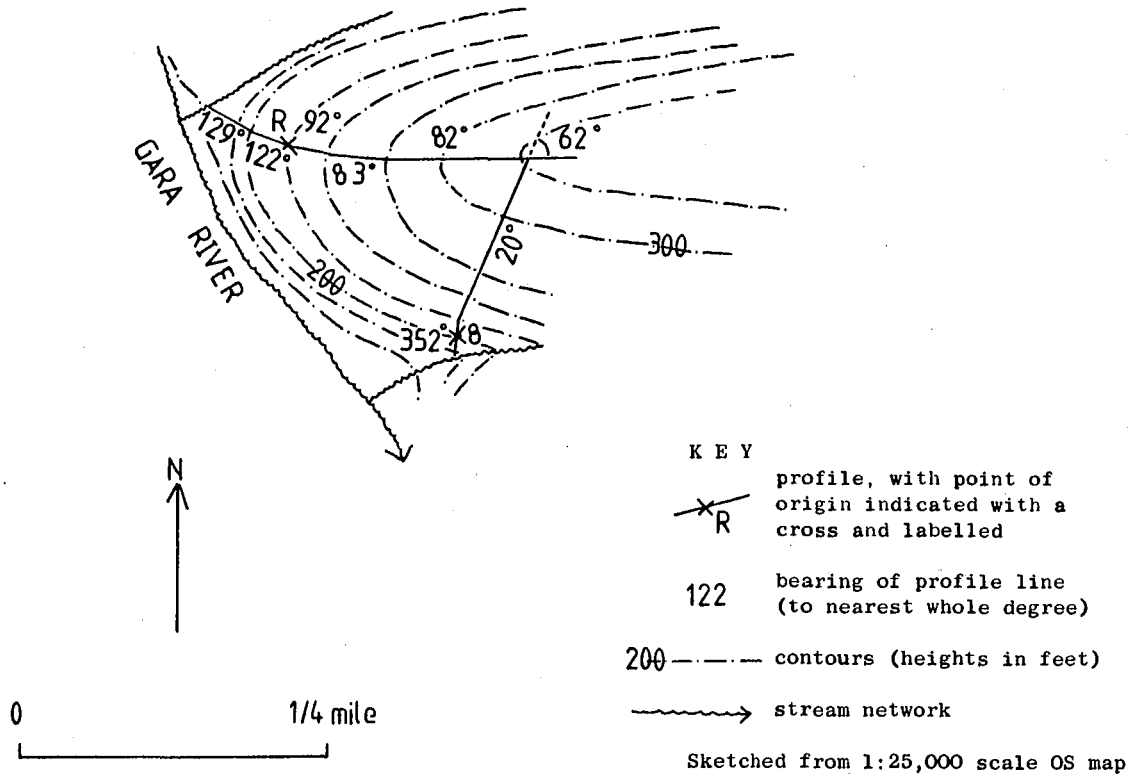


Figure 2.8 : Sketchmap of profiles R and 8 in the Gara catchment

catchment of interest, using a quantitative fitting procedure to be developed in future chapters. In some senses the computer-based problem is less difficult than the field one because the computer profiles are free to change orientation every ground surface length, whereas the compromise solution for this field survey was to keep to a constant bearing over six such lengths. Thus the field profile inevitably has to undergo some jerky changes in orientation, and the problem is to define an upper limit where jerkiness due to the method of measurement passes into an angular change due to significant true slope deviation. In the construction of the computer program, both 'local' (comparing orientation of measurement with that preceding it) and 'global' (comparing orientation with that established over the whole profile) differences were eventually built in to termination tests (chapter 4). Values of maximum local orientation change permitted in practice for each profile surveyed in the field are listed in the left-hand column of table 2.1, while the figures in the right-hand column of the same table put the local orientation change figures in perspective by showing the overall change in bearing achieved by the profile. Thus for example in profile 6 (at the bottom of the table) a change in bearing of 59° was made between successive ground surface lengths at one point; this was however due to interference in ground slope continuity caused by a farm track, and after that the profile was continued on a similar bearing to before. The change in bearing between first and final length was only 27°.

For profiles R (figure 2.8) and 10, measurement of plunging divides was involved while everywhere following true slope, which suggests that Young should not be so critical of Pitty's 'cut-off procedure' for not sampling crestal areas, as was mentioned in section 2.4. Profile 10 required a total angular change of only 16° to follow a plunging divide from the point of origin situated on a nose slope; it was

Table 2.1 : Changes in bearing in field profiles

Profile name*	Maximum difference in bearing between any 2 adjacent lengths along profile (degrees)	Difference in bearing between first and last lengths included (degrees)
4	0	0
7	0	0
11	0	0
13	0	0
20	0	0
A	0	0
B	0	0
D	0	0
F	0	0
G	0	0
M	0	0
Q	0	0
5	2	2
O	2	2
P	2	2
T	4	4
18	5	5
21	5	0
16	6	8
H	6	6
12	7	5
I & 15	7	7
L	9.5	9.5
1	10	10
10	12	16
N	15	15
9	18	21.5
8	28	28
R	30.5	47.5
J	47	32
19	57	69
6	59	27

* numeric : grid scheme; alphabetic : PSBL scheme

terminated at its upper end when slopes on either side of the divide were found to have an inclination steeper than that of the divide, which happened when the latter fell below 2°. The divide could then be said to have stopped plunging relative to its flanking valleysides.

2.8 iii Obstructions

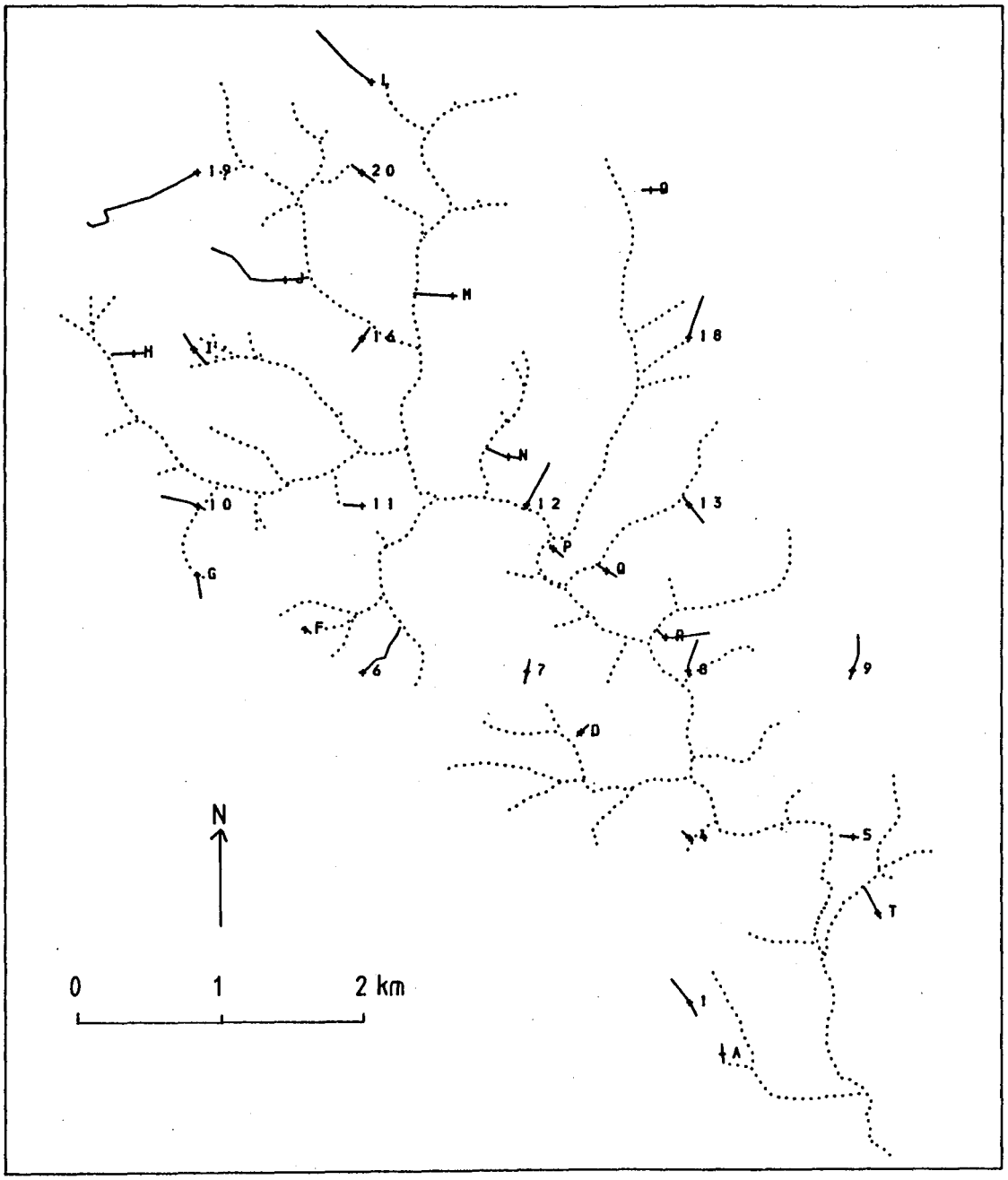
It was very difficult to profile across roads in this catchment, as they are mostly very sunken lanes flanked by dense hedgerows. Fortunately the main roads have been constructed along the gently-sloping watershed of the catchment, only a few crossing it from side to side; and roads follow only some parts of the Gara valley floor, not its entire length. Thus roads were occasionally the reason why a profile could not continue right to its crest or base, but never had to be crossed mid-profile. Hedgerows between fields did present some problems : usually the gradient and distance through them had to be guessed while the surveyor pushed a ranging pole through to mark the position and then walked round to continue the profile on the other side; occasionally a small offset was necessary.

Most farmers preferred survey not to be carried out through barley and cutting grass fields, so some profiles had to be moved or abandoned because of this (see table 2.2). (Due to the incompleteness of some profiles, figure 2.9 should always be consulted in conjunction with table 2.2). A different time of year for survey would have been wiser in this respect, but the fieldwork was originally planned to coincide with maximum daylength in the year and plans could not subsequently be changed.

In all 32 profiles were surveyed, two of these combining two points of origin in one profile (I and 15, K and 20), so 34 points of origin were 'successful'. (Although profiles B and 21, which had to be surveyed on the opposite valleyside slope to that chosen - for reasons

Table 2.2 : List of profiles in the Gara unsurveyable, incomplete, or offset, together with the reasons for this

Profile name	What was done	Why
(GRID SCHEME)		
2	no survey	landlord absent
3	no survey	crops
5	some talweg end missing	thick copse on lower slope
6	some divide end missing	crops
15 & I	"	crops
17	no survey	crops
21	surveyed slope opposite	crops
(PSBL scheme)		
B	surveyed slope opposite	tenant absent
C	no survey	crops
D	some talweg end missing	road
E	no survey	nudist colony
G	some divide end missing	road
I	see 15	
L	some talweg end missing	farmer's opposition
M	some divide end missing	crops
P	some talweg end missing	road
Q	some divide end missing	crops
S	no survey	crops



KEY

1 — profile (point of origin shown with a cross and labelled as in figure 2.4)

..... stream network

Figure 2.9 : Profiles surveyed in the Gara catchment

see table 2.2 - were eventually excluded from analysis, bringing the number of profiles down to 30). Since an object of the exercise was to compare profiles sampled from points of origin selected according to the two schemes, there was no point in measuring a profile very far off-course from the chosen one if the latter could not be surveyed for some reason (e.g. nudist colony, profile E!) This explains the incomplete sample : omissions do not appear to be preferentially located in any one area of the Gara however (compare figures 2.4 and 2.9).

2.9 Comments on survey according to the two sampling schemes

i. Grid scheme

With such a considerable area of the catchment occupied by low-gradient summits (figure 2.3), it was inevitable that some profile points of origin chosen by a 'surface-random' sampling scheme would fall on them. The created some problems in profile alignment, illustrated below with reference to profiles 11 and 6.

Profile 11's point of origin fell almost exactly in the middle of a crest from which slopes fell away on three sides; the direction of the profile to be measured downslope from it had to be decided by taking slope angle readings in the three principal directions. For two of these directions the reading was 0°; over the third, 1°, so the latter was chosen, leading to a small tributary valley at Seccombe rather than to the main river as the map suggested. (Visual inspection confirmed this direction : the quantitative evidence alone could have been caused by a localized hummock and needed support). This not only illustrates the importance of aligning the profiles in the field rather than solely from maps, but also the need to pinpoint exactly the point of origin in the field in such a situation. Although this was possible to some extent in the Gara catchment due to field boundaries, this must count

as a weakness of the grid scheme for this type of topography. Since the PSBL runs halfway between crest and divide, it cannot by definition give rise to crestal points of origin.

For profile 6 the point of origin lay upslope of a marked concavity (figure 2.4). It was clear in the field that a flowline leading from the point would end up in the concavity, the profile line changing course through an angle of 29° to reach it. A tentative conclusion would be that grid scheme profiles tend to undersample downslope noses in a landscape characterized by extensive summit areas. On the other hand a profile whose point of origin had fallen on the nose slopes on either side of the concavity in question (which would be the case with a PSBL-generated profile) would have terminated at the upper end of the nose where maximum slope angles were towards the concavity at 90° to that slope; thus the extensive area of crestal slope above this - traversed by profile 6 - would have gone unmeasured.

Some mention must be made here of the operational definition of local baselevel used to terminate profiles at their lower end. The concavity traversed in profile 6 would count as 'hydrologically sensitive' in the sense that in very heavy storms it could be a locus of overland flow, but it was considered here to be a hollow rather than a talweg at which a profile should terminate, because it sloped steeply (at angles of between 7 and 11° at its lower end, and more higher up), and because the profile did not have to swing through a large angle (over about 45°, see above) to follow it. Again this decision might have been taken differently by different workers : if everyone were to state the quantitative basis for such decisions however, differences could be reconciled and a standard for future fieldwork decided upon. Ahnert (1970) noted this problem and recommended that profile description start from crests because recognition

of profile bases involves these difficulties of definition. However in the Gara study the recognition of crests posed even greater problems. Profile 6 was continued to the stream (marked on the map with a blue line) in the valley bottom lower down. Profile 1 was terminated in the tributary talweg to which it led, although this contained no blue line on the 1:25,000 map either, for the opposite reasons : this talweg was gently sloping and made for an abrupt change in orientation of true slope path from profile 1.

2.9 ii PSBL scheme

A drawback of the PSBL scheme, as modified for this study to take less account of small first-order valleys, was that sometimes a point of origin would be located precisely on a stream channel, and there was a choice of profiles to extend upslope from it, as was the case for profile G - photographed for figure 2.10. The choice could have been made as for profile 11, by finding the maximum angle from the point in each of the three principal directions; in fact a broadly upstream direction was dictated by crop position, but appeared to be a good one. Nor was the grid scheme protected against such an occurrence, although it is less likely that a grid intersection will happen to fall on a stream. The points of origin of profiles I and 15 fell at Higher Cliston Farm, in an area of numerous sub-parallel channels, so both profiles interpreted strictly would have extended for a few metres to the nearest hummock and stopped. In the event, a profile was taken through the area occupied by both points, towards higher ground above the farm; again there was a choice of direction to take here, but unfortunately crops prevented completion.

The alternative of oversampling small valleys if a PSBL is taken all the way round a first order stream rather than crossing it (see discussion of figures 2.5 and 2.6 earlier) is more undesirable, for

profile point of origin, on stream, is marked with first red-and-white ranging pole (follow arrow to ½cm below lower hedge)

barley

barley

profile line in foreground : path of grass flattened by tape can be seen leading from here to second ranging pole

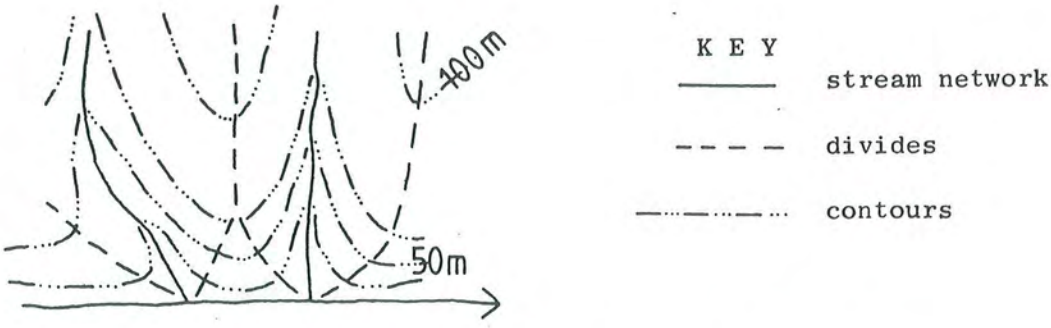
second ranging pole lies on profile line, in front of hedge with gates

Figure 2.10 : Photograph of the lower part of the Gara's profile G, illustrating a choice of path to survey from point of origin in a stream.

this study, than the problems encountered above due to points of origin falling on streams. Of the twenty points of origin in the PSBL scheme, 8 fell in valleys containing only first-order blue lines, compared with 9 for the grid scheme. This agrees with a rough visual estimate that 50% of the Gara catchment's area is first-order valleys, and is an indication that the PSBL scheme as applied here had not oversampled them.

The difficulty in drawing divides in many flat summit areas, mentioned in connection with the construction of the PSBL, was borne out in the field : several times fieldwork proved map-defined divides to be in error. The case of profile 11 has already been mentioned; also at the top of profile 18, what had appeared on the map to be a fairly substantial neighbouring valley (containing a blue line) turned out to be very localized in the field, and profile 18 stopped a few metres from its talweg. Profile M ignored two small tributary valleys which shared its hillslope but were not given divides in preparatory mapwork because they contained only very short blue lines. However the difference between these valleys and profile 18's neighbouring valley was less great than the blue line network implied. In the Gara catchment it is characteristic to have large areas of rounded nose slope at confluences, giving tributary divides like those illustrated in figure 2.12, rather than the more classic situation for maturely-dissected topography (figure 2.11). In the latter case it is much easier to decide on upslope termination of profiles than in the former case, but since the landscape of the Gara is not untypical for Britain, contingencies must be devised to deal with this situation, and were explained in section 2.8 ii.

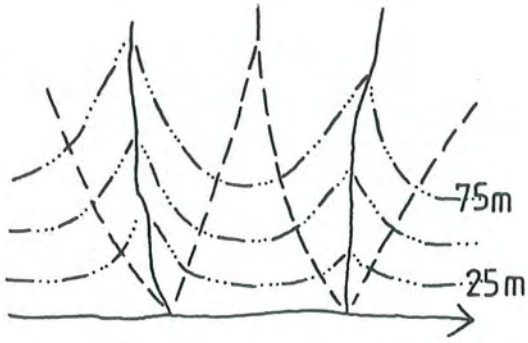
Non-crestal positioning of PSBL points of origin involves the risk that crestal slopes will be undersampled using the scheme, because after ascending a steeper lower-valley slope the crest would often appear



(A) Deep incision of tributary streams leaves small slip-off slope towards main stream.

(B) Relatively steep slopes, straight in plan, present few problems for profile survey : Gara catchment at site of profile B.

Figure 2.11 : The situation in 'mature' well-dissected topography with clearly-definable divides : illustrated diagrammatically (A) and with a photograph from the Gara (B).



K E Y
See figure 2.11.

(A) Substantial nose slope drains to main stream (compare with figure 2.11 A).

(B) Lower three-quarters of profile 4 : the profile point of origin was near fence shown in foreground; downslope from it was fairly straightforward, but shortly upslope a plunging divide was encountered and the profile had to stop.

Figure 2.12 : The situation most usually found in the Gara catchment, with incomplete dissection by streams : illustrated diagrammatically (A) and with a photograph from the Gara (B).

to be sloping approximately at right-angles and profiling would be terminated. With crestal location of points of origin - as in the extreme with profile 11 for example - the surveyor is forced to find a path of maximum descent over the crest and into a valley.

2.10 Conclusions on profile survey in the Gara

Many of the greatest difficulties with the PSBL scheme arise before the fieldwork : divide and PSBL construction are inevitably somewhat arbitrary. The resulting profile point of origin locations using the PSBL are satisfactory except where points fall on a stream path, which is quite likely with the necessary modification suggested in this study, to the effect that the line takes less notice of first-order streams.

Table 2.3 columns 1 and 2 show selected summary statistics for land form attributes as estimated by sampling by profiles according to PSBL and grid schemes. The data suggest that greater sampling of crestal areas has been achieved with the grid scheme profiles to give the lower figures for mean and standard deviation of gradient than the PSBL's. The positive skew of the gradient data accords with the visual impression of the Gara as predominantly gently sloping with steeper slopes localized nearer streams. The agreement between grid and PSBL datasets for standard deviation of profile curvature is very good, indicating that this attribute is not sensitive to the difference in degree of crestal coverage between the schemes suggested by the gradient figures. More conclusions are drawn from this field data in chapter 5 where comparisons with matrix statistics are carried out.

Some of the problems encountered above using both schemes could be avoided by omitting the low-angled summits of the Gara from the sample altogether. If 'acting divides' were to be drawn around the summits where slope angles were predominantly below some threshold

Table 2.3 : Summary statistics from field-measured profiles

		Gara, PSBL profiles (gsl*=5m)	Gara, grid profiles (gsl=5m)	Netherhearth profiles (gsl=1.52m)	Netherhearth profiles (horizontal constant length = 5m, interpol - ated)
gradient (°)	mean	8.14	7.78	7.64	7.38
	st.dev.	5.90	5.45	6.07	3.85
	skewness	1.16	1.05	1.60	0.60
	kurtosis	0.37	0.71	5.58	2.51
	max.	25.00	30.00	45.00	22.07
	min.	0.0	-2.00	-13.00	-7.39
profile curv- ature (°/100 m)	mean	2.18	1.89	8.32	8.20
	st.dev.	23.77	23.26	235.04	51.67
	skewness	-0.39	-0.23	-0.20	-1.04
	kurtosis	12.04	8.95	5.57	4.43
	max.	175.00	165.00	1266.45	144.54
	min	-135.00	-140.00	-1282.89	-238.17
No. of measure- ments		765	907	822	216

* gsl = ground surface length for each gradient measurement.

value, the PSBL could be constructed half-way between these 'divides' and the blue line. Grid scheme points of origin would be constrained to fall outside the low-gradient area, and survey in the field in both cases would stop at the previously-defined acting divides, thereby avoiding the problematic decisions over upslope termination. Although the choice of cut-off angle would be somewhat arbitrary, in the Gara it is about as easy to identify the break of slope between summits and valleysides as it is to guess the position of a watershed on contour-sparse hilltops. The advantage of the approach to be advocated in this thesis, where profile and matrix information are to be combined, is that information on land surface form in the areas unsampled by profiles could still be provided, by the matrix.

Such a solution would not be necessary for profiling in more 'well-behaved' topographies where watersheds are more clearly-defined - witness Ahnert's (op.cit.) description of the upper end of the profile as 'unmistakeable'. However, a morphometric method should at least be applicable to all landscapes of a broadly-defined type, in this case fluvial landscapes; procedures for use in more difficult terrains need some consideration in the literature on profiling.

2.11 Plan curvature

This study aims to provide ground truth data for comparison with an altitude matrix, in three dimensions. Therefore field measurements of contour (or 'plan') curvature, by definition at right-angles to true slope lines, were also carried out. In the Technical Bulletin, Young (1974) suggested a method of measurement which was followed in this study : align three ranging poles along a contour (by registering clinometer readings of 0°), the central one standing on the profile line and the flanking two 20 m distant on either side of it. Measure with

prismatic compass the angle subtended at the central pole by the two flanking ones, taking the angle lying away from the slope. This is converted to the standard expression for plan curvature by the following formula

$$P = 5(\phi - 180)$$

where P is plan curvature in degrees per 100 m

ϕ is horizontal angle subtended at central rod by two lateral rods (ibid, 38).

One modification and one addition to Young's suggestions were made here. The modification was that measurement of plan curvature was not restricted to the steepest part of the slope as Young suggested, since Parsons (1979) found that this gives an underestimate of average plan curvature for a slope. Parsons recommended measurement instead at the PSBL, if only one measurement of plan curvature per profile is to be made. Measurements were taken in this study at a station near the middle of the profile and sometimes in one additional location along the profile, if this appeared to be very different in plan from the first place. It seemed to this researcher that it is difficult to characterize any slope with one measurement of plan curvature : an orthogonal that starts on a gentle summit and later descends into a hollow (such as profile 6 in the Gara), for example, will encompass a broad range of plan curvature in its path. Since measurement of plan curvature in the field is so time-consuming, and requires a swathe of land 40 m wide to be uninterrupted by obstructions such as field boundaries, it was not possible to make very many such measurements in this study. Consequently it is not presumed here to make recommendations on the sampling design of field measurements of plan curvature : the measurements taken in this study provide a limited field comparison with matrix-derived estimates of this attribute, described in chapter 5.

The addition made to Young's procedure was that plan curvature was measured in the Gara over 10 m lengths either side of the profile as well as 20 m, to give some indication of the effect of scale of measurement. In the event of a hillslope having perfect radial symmetry, results from the two lengths of plan curvature measurement would be the same when multiplied up to be expressed over 100 m. Figure 2.13 shows that this is not widely the case in the Gara, although the two sets of figures - predictably - are highly correlated (partly due to the influence of the three extreme values). Troeh (1964, 1965) has had some success in fitting a radially-symmetrical model to pediments in the United States; these, however, differ considerably from slopes in the Gara. The calculation of profile curvature from angle measurements employs a similar formula to that for plan, and since few hillslopes are likely to be circular in vertical section (Troeh fits a parabola in this dimension), it means that results obtained for profile curvature are even more likely to be heavily dependent on ground surface length measurement used in survey. This statement is tested below.

Figure 2.13 also shows that only three of the slopes on which plan curvature was surveyed in the Gara would be classed as 'relatively straight in plan' (defined in section 2.7 ii) by both 20 and 10 m measurements. A restriction to such slopes would therefore have rendered the majority of the profiles chosen by grid and PSBL schemes unworthy of survey.

2.12 Netherhearth Sike catchment : topography and drainage

Netherhearth Sike's catchment area of 1.3 km^2 extends from an altitude of 743.5 m at its southern watershed, to 557.5 m at its confluence with Moss Burn (which later joins Trout Beck), a range in height of 186 m. The catchment forms a strip of land (figure 2.14)

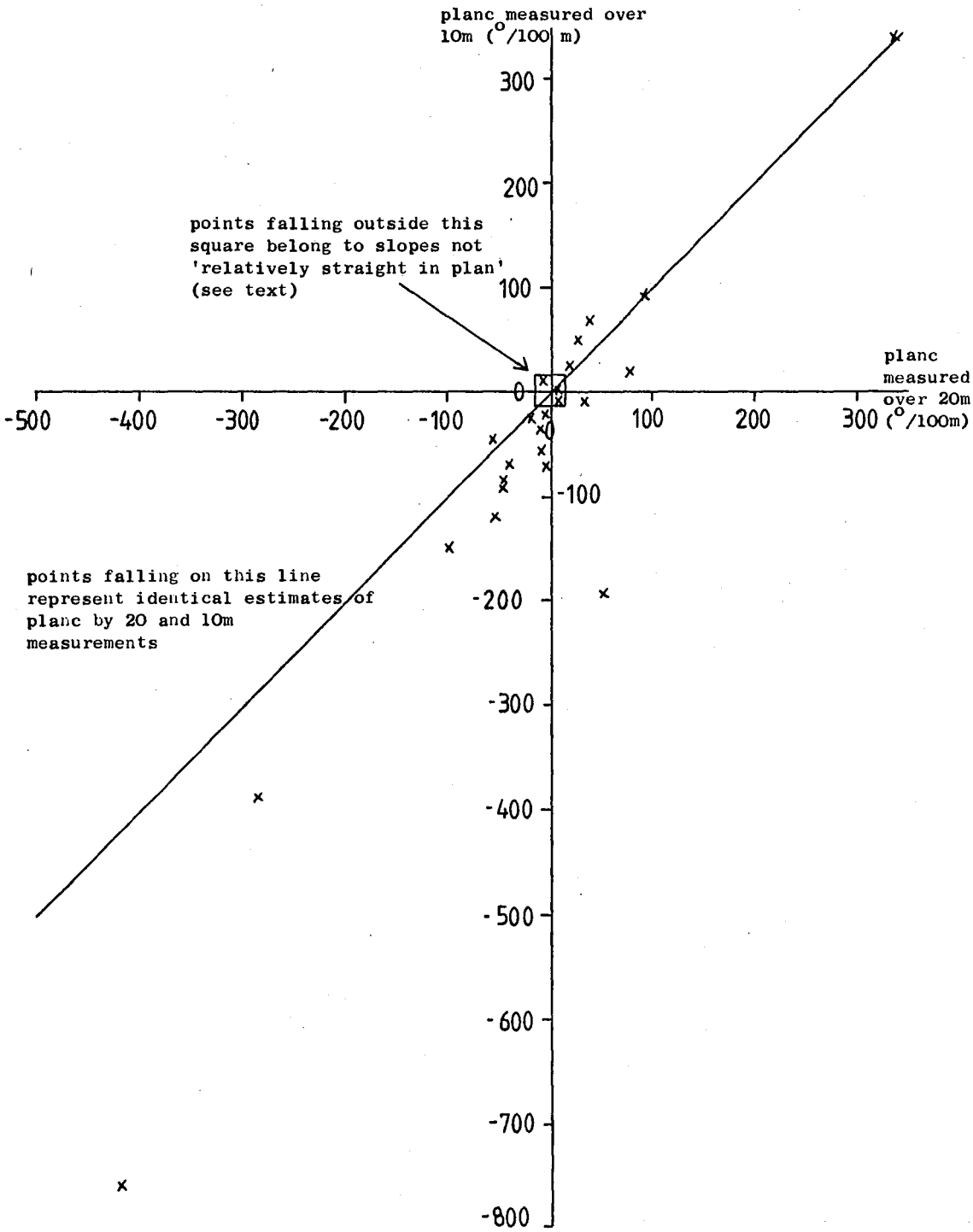


Figure 2.13 : Scatterplot showing relationship between plan curvature as measured over 20 m and over 10 m either side of profile line.

K E Y

Direction of arrow signifies aspect, length of shaft of arrow signifies magnitude of gradient, thus

shaft length	gradient class limits
0.0 mm	less than 2.60°
0.8 mm	2.60 - 3.99°
1.6 mm	4.00 - 5.39°
2.4 mm	5.40 - 6.79°
3.2 mm	6.80 - 8.19°
4.0 mm	8.20° and over

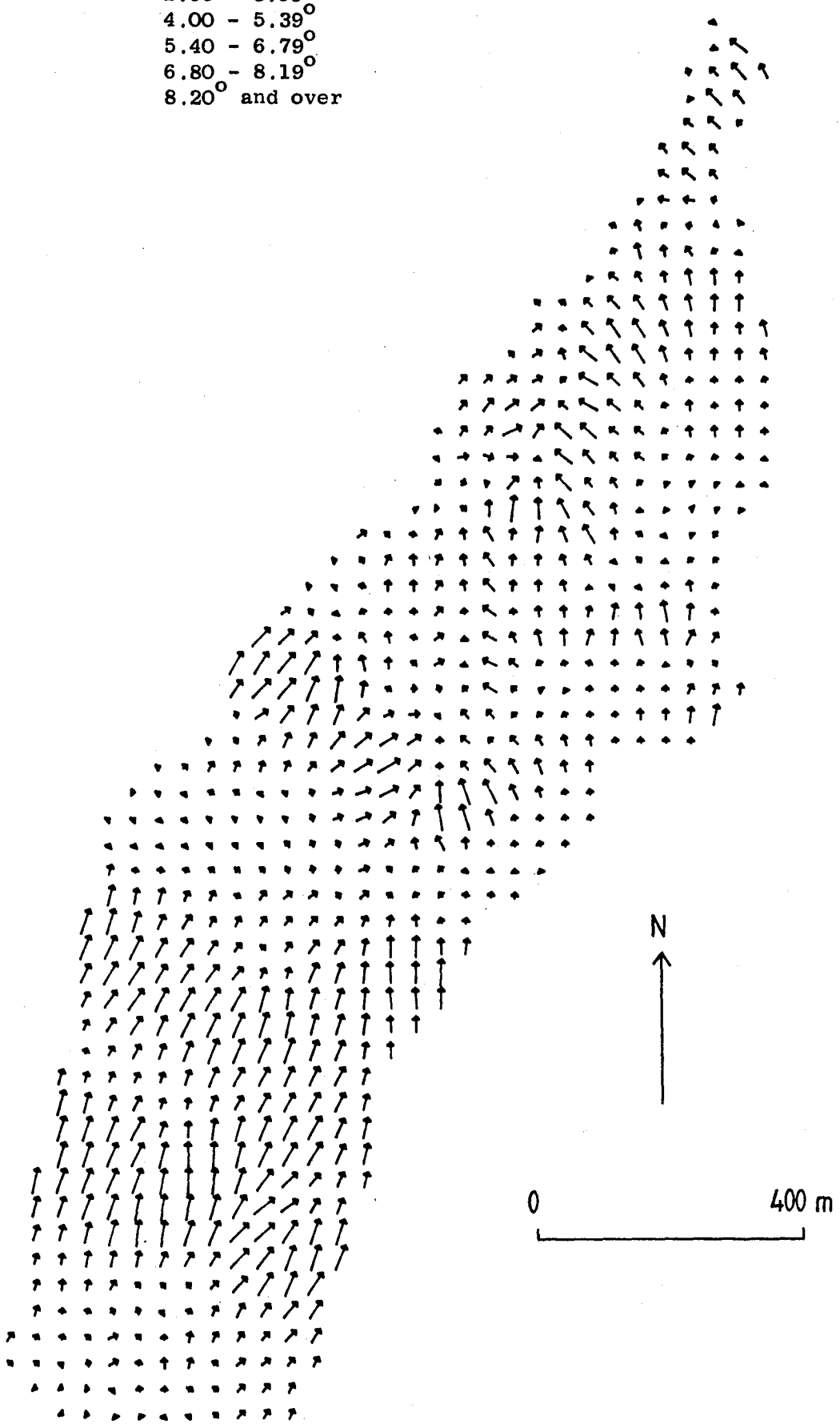


Figure 2.14 : Distribution of gradient and aspect over Netherhearth catchment, from altitude matrix data at 40 m mesh.

descending the southern side of Trout Beck's rather bowl-shaped drainage area. The relatively short southern edge of Netherhearth catchment is made up of a portion of the low-gradient watershed of Trout Beck and is characterized by chaotic drainage and peat haggs, representing a typical example of Bower's (1960) type 1 peat dissection, which she states will only take place on ground sloping at an angle of less than 5°: the gradient here is less than 4°. Thereafter the ground dips much more steeply towards the north at angles of 8° or more, over which the Sike flows as a series of parallel channels. Over the lower two-thirds of the catchment's length, the northward regional slope is gentler and the Netherhearth has carved a small valley for itself, flanked by steeper slopes which show up on figure 2.14. It has a flat floor over which the stream meanders in its lower reaches. Still towards the eastern and western edges of the catchment the regional slope is apparent at angles of 2-5°.

The generally subdued relief of the area is disturbed at a detailed scale by the channels and by numerous, often sub-parallel ditches, typically 1-2 m deep, some of which qualify as 'peat flushes' (figure 2.15). Peat flushes are defined by Burt and Gardiner (1982) as channels that do not contain unvegetated channel troughs, and which flow only during periods of storm runoff generation rather than perennially. They are distinguished from channels eroding <u>into</u> the peat, because the latter are not vegetated (Ingram, 1967). These storm channels are clearly of interest hydrologically, but their topographic expression would not be detectable from an airborne survey (although a plan drawing of their courses could often be made from such a remove). More comment is made on this issue in chapter 3, where field survey of a matrix of part of this area is described.

The geology of the catchment is composed of the middle limestone

Figure 2.15 : 'Peat flush', Netherhearth catchment.
(For definition see text)

The photographer was standing in one of these ditches, which leads downward to Netherhearth Sike (flowing right to left across middle of picture, by standing figure).

group of the lower Carboniferous (Johnson and Dunham, 1963), consisting for the most part of an alternating sequence of limestone and shale outcropping in bands roughly parallel to the terrain contours. Some sandstone outcrops towards the southern watershed of the catchment. The parts of the catchment in limestone are distinguished by the presence of closed depressions and the more gorge-like nature of the sides of the Sike developed in this rock.

2.13 Measurement of selected slope profiles in Netherhearth catchment

From an examination of the topography of the catchment it appears that there are two types of profile to be sampled in this immaturely-dissected area : the regional slope towards the north, and the slopes of the Sike's localized valley. The two types trend roughly at right-angles to each other. There are other localities, such as the headwater area of peat haggs and gentle overall slope, in which profiling cannot realistically be carried out at all.

By locating profile points of origin randomly or systematically in the catchment and eliminating 'no-slope' areas, a population of profiles could have been surveyed which included these two major types. The construction of a profile sampling baseline would have involved numerous problems given the many channels and poor dissection of the area. Young (1974) recommends use of the talweg to define points of origin in open ground; this would be feasible in the lower, more well-defined section of the Netherhearth valley, but not in the area of parallel channels higher up.

It became clear from a pilot study, however, that it was almost impossible to locate points marked on a map in the field here, since there are no field boundaries to assist as in the Gara, and channel configuration had clearly changed substantially since the aerial

survey from which the map used in fieldwork was prepared in 1969. There are few well-defined topographic contrasts to aid in this matter either, and the only landmarks from which bearings could have been taken are the masts on Great Dun Fell at the western extremity of Trout Beck, and the Nature Conservancy buildings, neither of which was visible for much of the time in the poor weather conditions to which this area is subject. For these reasons a full profile survey following a defined sampling pattern as in the Gara was not undertaken here, but members of the two slope types were surveyed (see map, figure 2.16).

A method of profile measurement had to be devised. The short valleyside slopes are suited to use of the pantometer of 1.52 m ground surface length designed by Pitty (1968), off which slope angles can be read to the nearest $\frac{1}{2}^{\circ}$ on a protractor scale. The path to be measured was first defined by laying a brightly-coloured rope along a steepest descent line, as it is time-consuming to check the direction of true slope after each pantometer reading. For the long, regional slope (profile 15), a short measured length was not necessary, and although the pantometer was used for this profile also to give consistency to the whole survey, the recording of a long series of practically identical angle readings seemed highly redundant. The arguments for standardizing ground surface length used in profiling are very persuasive and have already been set down (section 2.4); the findings of the Netherhearth survey suggest however that it can be difficult to decide on one ground surface length to be used throughout one area, and so it seems inappropriate to limit surveys in all topographies to one format. It is more sensible to recommend a selection of standard ground surface lengths to be used in surveys as Young does : 'where 5 m is unsuitable, 2 m, 10 m or 20 m should be used' (1974, 33). The surveyor should adhere to one measured length throughout a particular surveyed profile, and

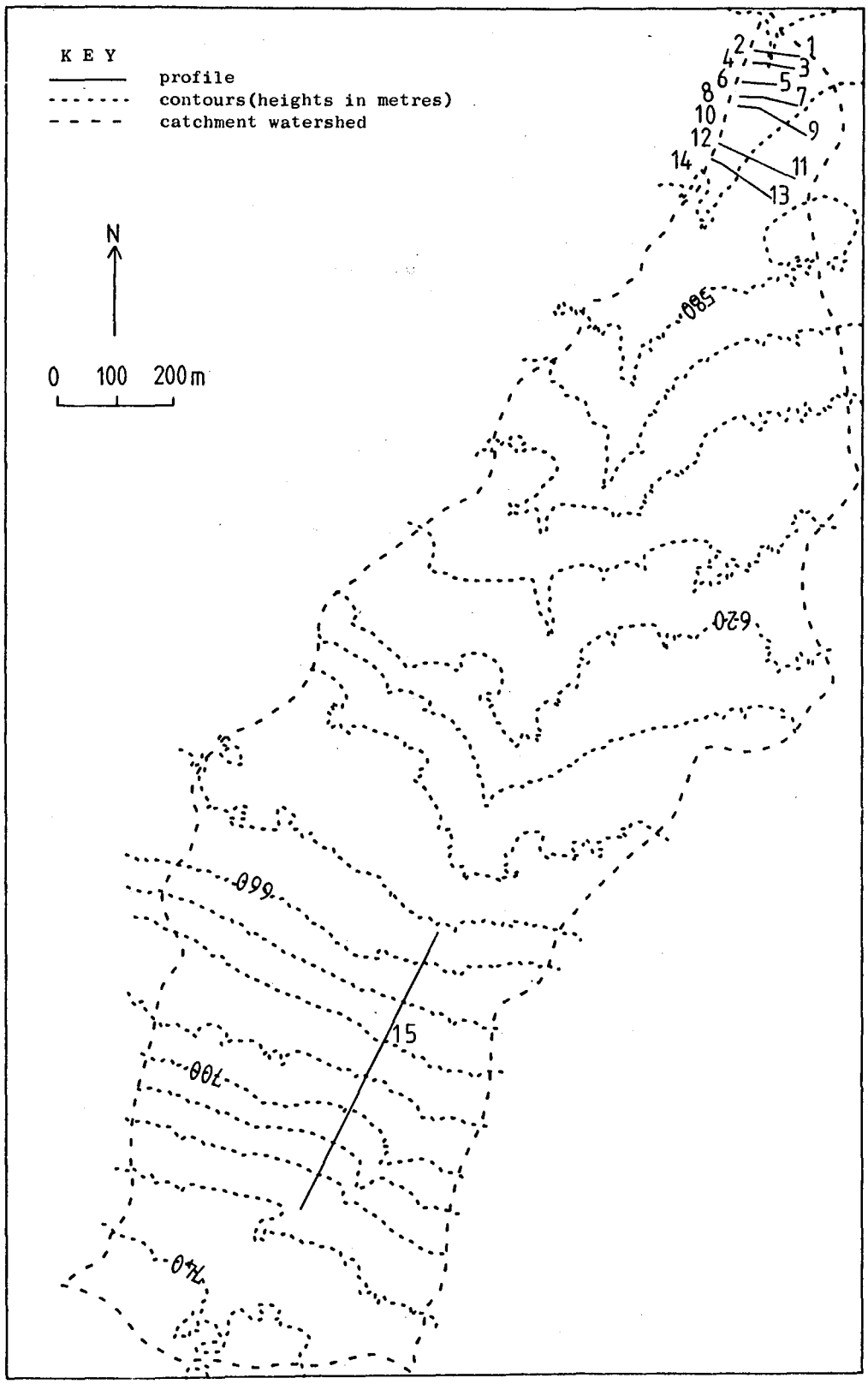


Figure 2.16 : Profiles surveyed in the Netherhearth catchment

take care to state the length used during all subsequent presentations and calculations involving the data.

The vegetation mat in this moorland area is very dense, so that although a man stands on top of it, the pantometer's feet sometimes tended to stick down between stems : in this survey all measurements were made with pantometer feet standing on top of vegetation, since it was often difficult to reach the ground beneath thick tussocks. For this reason some larger tussocks of vegetation (maximum height noted ½ m) may have added to or detracted from the local ground slope; the series of angle measurements therefore incorporates this vegetational'noise'.

Again the problem of profile termination at their upper ends was encountered. As in the Gara, the Pitty method was favoured over Young's (see discussion, section 2.4), as it seemed pointless to continue a straight line of profile recording angles at 0 and 1° when the ground plainly sloped in a different direction and only true slope readings would be used in subsequent analysis. In Netherhearth it was possible to sample crestal areas also, by surveying a profile in the localities upslope from the Sike where true slope descends towards Trout Beck rather than towards the Sike itself; such a profile would tend to end in a tributary transverse to the Sike, as did profile 15.

Profiles 1 to 14 were surveyed at close intervals measured along the Sike's valley floor (figure 2.16), 15 m spacing being typical. This contrasts with the Gara survey, and is even closer than the 200 m spacing used by Parsons. In the next section, Gara and Netherhearth profiles will be compared statistically with their neighbours, to evaluate the effect of profile sampling density on the land form information obtained.

2.14 The issue of similarity between adjacent profiles : comparing Gara and Netherhearth

Since the Gara profiles were mostly surveyed at much greater distances from each other than the Netherhearth profiles, it was judged that comparisons between the two sets of data could yield information on the optimum density of profile sampling to prevent replication while ensuring coverage of all slope types.

For every profile, the gradient value for each of its component ground surface lengths (gsl's) was paired with that for the equivalent gsl belonging to its neighbouring profile (pairing of lengths started at profile bases as these are most reliably located, given the problems of upslope termination). The mean and standard deviation of the differences between gradient pairs were found for the profile pair as a whole, and are displayed in figure 2.17.

It is clear from columns 1 and 2 of this figure that by this method of reckoning, adjacent profiles in the Netherhearth are less similar in pairwise angle measurements than are the Gara's more widely-spaced profiles. This undoubtedly owes something to the greater variability in angle measurements in the Netherhearth imparted by a shorter gsl (1.52 m as opposed to 5 m in the Gara). Column 4 of figure 2.17 shows figures for gradient that would have been obtained had 5 m horizontal constant lengths been used in the Netherhearth (calculated by linear interpolation between field profile stations). This modification decreases mean and standard deviation of gradient differences for adjacent profiles to values more similar to the Gara's. (It should be noted that the number of these measurements obtainable from the Netherhearth profile dataset was not large, so great reliance should not be placed on these statistics : they give an indication only). The smoothing effect of increasing ground surface length is also borne out

A) Mean angular differences (degrees)

(1) Gara (5m gsl)		(2) Netherhearth (1.52m gsl)	(3) Netherhearth 1.52 m gsl, every other profile	(4) Netherhearth 5m horiz. constant length (interpolated)
94	1 ·			68
98	2 ·			01
77600	3 ·			5
995100	4 ·	48		4
9740	5 ·	6	3	
984	6 ·	46		9
931	7 ·	16		1
7	8 ·	02	1	
1	9 ·		3	188
	10 ·			
9	11 ·		2	
6	12 ·			3
	13 ·	3	5	
	14 ·	9		
	15 ·			
	16 ·	0	3	

B) Standard deviation of angular differences (degrees)

8	0 ·			
82	1 ·			3458
865541	2 ·			
98864320	3 ·			04
9830000	4 ·	24	5	08
75210	5 ·	4		
	6 ·	3599		7
	7 ·	24	24	38
	8 ·	4	9	
	9 ·		7	8
	10 ·	5	6	
	11 ·			
	12 ·	1		

Figure 2.17 : Stem-and-leaf plots* showing mean (A) and standard deviation (B) of differences in gradient between equivalent ground surface lengths in adjacent profiles, Gara and Netherhearth catchments.

* This way of displaying data was conceived by Tukey (1977). The figures inside the 'stem' (indicated by two vertical lines close together in this figure) denote the whole-unit component of each data value, while the individual numbers in the 'leaves' (displayed in 2 sets of 4 columns in this figure) refer to the first digit after the decimal place for each data value.

by the summary statistics in table 2.3 (columns 3 and 4), in which it can be seen that increasing measured length in the Netherhearth from 1.52 m to 5 m (horizontal constant) brings standard deviation of gradient down from 6.07° (a figure greater than that obtained by profile survey in the Gara, a catchment twenty times the Netherhearth's size) to 3.85°.

Given that Gara and Netherhearth data were not directly comparable because of different length measurements used, tests were carried out to see if similarity within the Netherhearth profile dataset varied with distance apart of profiles. Column 3 of figure 2.17 shows the result of comparing every alternate profile (i.e. profiles 1, 5, 9, etc. - see figure 2.16) along the valleyside. This modification does seem to increase dissimilarity, although not drastically. Profile 15 was left out of the data presented in figure 2.17 altogether, as it was not part of the sequence of profiles 1 to 13 and 2 to 14 measured along the Netherhearth valley. The average difference in gradient between its lower end and profile 13 was only 5.10°, and between its lower end and profile 14 7.90°, standard deviations being 5.58° and 5.51° respectively, all of which would have plotted towards the centres of the histograms on figure 2.17. This implies that the greater separation of this profile did not cause an appreciable increase in dissimilarity. It would seem that the short ground surface length measurement used in the Netherhearth, capturing as it does the large amount of variation in that area at a detailed scale due to peat haggs and flushes, almost totally overrides any effect of increasing similarity due to greater proximity of profiles.

From the Gara data it is possible to take this argument one stage further to state that it is not proximity per se, but rather the similarity in terrain traversed by two profiles that will increase their similarity as measured by the method used here. Thus profiles 19 and 20

have small mean and standard deviation of gradient differences at 1.4° and 0.8° respectively, although not surveyed in the same valley (figure 2.9), because they were both measured in the predominantly gently-sloping headwaters of the river Gara.

Since this section has shown, above all, the importance of scale of measurement to results obtained, it is relevant to point out the sensitivity of profile curvature values to scale shown up in table 2.3. The change from 1.52 m gsl's to 5 m horizontal constant lengths decreases the standard deviation of profile curvature in the Netherhearth by a factor of 4½. This is confirmation that the observations made in section 2.11 on the scale-dependence of plan curvature values apply also to profile curvature measurements.

2.15 Conclusions on slope profile survey in the field

The first conclusion to be drawn from these surveys is that construction of the profile sampling baseline would only be straightforward if one were sampling one valley, which had sharply-defined divides, and if one were not interested in sampling the plan concavities at the head end of that valley. For a valley system, guidelines as to how or whether to sample the noses of land between stream junctions are lacking. For land with extensive flat summits, it is not clear whether to draw the PSBL between a guessed position of watershed and the river, or whether to treat the whole summit area as a swathe of watershed and take the PSBL half-way between the downslope limit of that and the river. If one is to sample plan concave areas at valley heads, it is not clear how far above the stream head the PSBL should be taken : this makes a great deal of difference to the chances of selecting a point in this area when sampling (see figures 2.5 and 2.6). The decisions made in these three situations have been made explicit here : for stream

junctions, the PSBL was not taken right down to the confluence, leaving nose slopes under about 100 m long potentially unsamplable. Divides were drawn over flat summit areas as if definable as a line, but reservations about this were expressed. The PSBL was not allowed to take a large detour around first-order valley heads, being constrained to parallel the contours roughly here.

Additional uncertainty hinges on whether to use the blue line or contour crenulations to define talwegs. If the latter course is taken, an arbitrary point has to be defined at which one decides to call one set of concave contours a talweg and another set a hollow. If the blue line option is taken, as was the case in this study, arbitrariness is again introduced in that the extent of the network in agricultural areas can reflect the diligence of farmers in draining or not their low-lying fields. More will be said on this subject in chapter 6 where a second interpretation of the PSBL is attempted.

Given these difficulties with the PSBL, it would need to demonstrate some convincing advantages to justify its use in preference to a grid scheme of profile sampling, which encountered none of these problems. The comparability between results from the two schemes is a theme running through much of this thesis, and conclusions will be drawn in later chapters in the light of data from matrices.

Another set of problems encountered with slope profiling in this sampling study stem from the fact that the method was first conceived as a way of obtaining graphical representation of vertical sections through the landscape, for which orthogonality to contours is desirable over the majority of the profile, but not essential everywhere along it, so that in most studies the simplifying option of measuring a profile along one bearing can be adopted. The lack of guidance as to how to terminate curving profiles at divides for a study where orthogonality

to contours is vital for process relevance, necessitated the introduction of a rule of thumb in the Gara : an abrupt change in direction of over 45° would usually lead to termination of survey. Different values would be needed in catchments of very different topography to this, or in studies using measurements of a different resolution. This subject is explored with matrix-based profiles in later chapters.

Another limitation of the method was practical : in areas of equable climate such as the Gara's, intensive agricultural land use leads to problems of accessibility. On the other hand, moorland areas like the Netherhearth are easily accessible, but have a climate that drastically lowers visibility for much of the time, and a dearth of landmarks with which to locate a point of origin. Profile surveys in both types of area will therefore probably lack some aspects of coverage : data from another source, the altitude matrix, are needed to indicate the full range of land surface attributes. This study is not the only one to have found difficulties with slope profiling, as the following quotation from Gerrard illustrates : 'The apparently simple task of slope angle measurement has been shown to present a number of vexing problems' (op.cit., 608).

The force of all these arguments is not intended to be negative regarding slope profiling : On the contrary, much of value to geomorphometry has been learned over the years of geomorphologists using this method ; for example, about the influence on results of the ground surface length used, to which this study has added further evidence. The use of simple instruments enables one surveyor to produce data of acceptable quality from most landscapes, and the widespread use of the method by geomorphologists means that the results of any one study can be evaluated in the context of others. This study has pinpointed the need for more explicit guidelines on profiling so that the geomorphologist

does not end up fudging important decisions when time is pressing in the field; it is also important that geomorphologists state what choices they have made (where there is a choice) as they are becoming accustomed to doing for measured length. The choices taken here will be critically evaluated with data from matrices to enable final recommendations on field profile survey to be made. First however the construction of altitude matrices is described in the next chapter, and ways of using information from them to yield results comparable to field profiling in chapter 4.

2.16 Notation

P plan curvature in degrees per 100 m

ϕ horizontal angle obtained in field measurement of plan curvature

CHAPTER 3 : CONSTRUCTION OF ALTITUDE MATRICES AND ANALYSIS WITH 'G'

3.1 Introduction

3.2 Discussion of appropriate methods of matrix construction for study areas

3.3 Construction of an altitude matrix of the Gara catchment by manual interpolation

3.4 Construction of an altitude matrix of Netherhearth catchment by digitising contours and interpolation using GPCP

3.5 Construction of an altitude matrix by levelling, within the catchment of Netherhearth Sike

3.6 Construction of a matrix of the levelled square, using GPCP

3.7 Program 'G'

3.8 Comparison of levelled and GPCP-made matrices for the same area

3.9 Overview of matrix construction methods

3.10 Gara and Netherhearth matrices analysed with 'G' : evidence on the influence of scale

3.11 Conclusions and recommendations

3.12 Notation

3.1 Introduction

As was stated in chapter 1, the digital terrain models to be used in this thesis are altitude matrices, in the form of square grid patterns of spot heights. In this chapter the construction of two large matrices, for the Gara and Netherhearth catchments already described in chapter 2, will be discussed ; one of these involves manual interpolation, while construction of the other was computer-assisted. The theme of contrasting matrix construction methods will be taken further by comparing a matrix made of one small part of Netherhearth catchment by field survey, with the basin-wide matrix made using the computer-assisted method.

In chapter 1 mention was also made of 'G', a computer program written for the purpose of 'statistical characterization of altitude matrices by computer' : this program has already been extensively described and tested (Evans, 1979). This research will make much use of it, starting in this chapter by investigating the issue of scale of measurement (as was done for profile data in chapter 2) by processing matrices at different mesh sizes.

3.2 Discussion of appropriate methods of matrix construction for study areas

There is a growing literature on the use of altitude matrices, often for the production of elevation contours on maps. They have become popular partly because they are readily yielded as a by-product of highly-automated orthophoto production, as in the Gestalt photomapping system. The main focus of many articles in such journals as Photogrammetric Engineering and Remote Sensing is therefore not on how to generate a matrix, as this is given, but on how best to contour from matrix information. For the average geomorphologist, however, the necessary equipment for this degree of automation in matrix production is seldom available, and it is

to such a researcher that the following accounts of the construction of matrices for this thesis are addressed. Compared with the more direct photogrammetric procedures, starting from maps interposes an extra stage, at which inaccuracy is bound to creep in, between the air photography and matrix construction : but it should not be inferred that the methods of matrix construction used here are necessarily inaccurate. They are heavy on the use of a researcher's time however, and would not therefore be considered by large commercial organizations who could write off the costs of machinery against labour.

The 1.3 km^2 Netherhearth catchment is covered by a photogrammetric 1:2,500 scale map with contours at intervals of 2 m. The contours run predominantly east-west across the catchment : there are few closed contours, and no contours come very close together. It was therefore judged that it would be fairly easy to digitise the contours and use a computer package to interpolate a grid pattern of altitudes from them. The package chosen was Calcomp's General Purpose Contouring Program (GPCP) available on the IBM 370 machine at Newcastle; GPCP has received favourable write-ups by other workers such as Young and Isbell (1978) and Welch and Jordan (1983). This semi-automated method of matrix construction is outlined in detail in section 3.4.

A grid mesh of 10 m on the ground was chosen as being the finest that the Netherhearth map would justify, given the wide spacing of contours in some parts of the area where a more detailed mesh spacing would have created a false impression of precision. This falls comfortably outside Mark's lower limit for justifiable mesh size of 4.29 times the contour interval (quoted in Peucker, 1980).

The most detailed contour map coverage available for the 27 km^2 Gara catchment is the Ordnance Survey's 1:10,560 scale map, with contour interval 25 feet. The contours on this map are closely spaced in places

and would be difficult to digitise; the scarcity of contours on summit areas would also create problems for computer interpolation to an altitude matrix grid. A completely manual method of matrix construction was therefore chosen, described in the next section. The mesh size used was 50 m, again judged to be the greatest detail allowable, given uncertainty in the areas of sparse contours; this again falls outside Mark's lower limit which would be 32.69 m for a contour interval of 25 feet.

In addition a 100 m x 100 m square of Netherhearth catchment was surveyed in the field at 10 m mesh by levelling, an exercise designed to gauge the accuracy of the computer-assisted matrix construction of the same area at the same grid mesh. The field method is described in section 3.5.

The matrices constructed in this research are classified in table 1 for easy reference.

3.3 Construction of an altitude matrix of the Gara catchment by manual interpolation

First the watershed had to be drawn round the catchment, which involved some problems on the flat summit areas discussed in chapter 2. A grid was then constructed at a mesh size equivalent to 50 m on the ground, and photographed onto non-deformable transparent material so that by laying it over the map the positions of the grid intersections (altitude matrix vertices) on the contoured surface could be seen and their height determined by interpolation between the nearest contours. Heights were recorded for all vertices falling within the watershed, and for the single layer falling outside it all the way round, the latter being needed for 9-point quadratic fits using 'G' (see section 3.7) for the points immediately inside the watershed. Heights were recorded, in rows starting at the north-west corner of the map, straight

Table 3.1 Matrices constructed

	Netherhearth Catchment		Gara Catchment
area covered	1.33 km^2	0.01 km^2	27 km^2
map-derived matrices made	10 m mesh (with dig. contours & GPCP) 150 x 235 points*	10 m mesh (with dig contours & GPCP) 11 x 11 points	50 m mesh (by manual interpol.- ation) 160 x 162 points*
field measured matrix		10 m mesh (by levelling) 11 x 11 points	

* The number of points quoted here is for the rectangular area covering the drainage basin.

on to coding forms for input into the computer as an altitude matrix.

In areas of steeply or uniformly sloping ground, judgement of heights at grid points simply involved linear interpolation between adjacent contours. Towards the summit of a hill gradient would often be decreasing, and where the contour spacing suggested this it was taken into account in interpolation. On contour-sparse summits, however, the decisions were more subjective : even trigonometric points and spot heights were of limited help here as the Ordnance Survey are more concerned with intervisibility than with demarcation of a local summit, and most spot heights are located along roads. Decisions on hilltop areas thus had to rely on what Evans called 'intuitive interpretation of relief, e.g. the rounding of summits and the presence of some flat-topped ridges' (Unpublished Report, 1982).

Along the valley floors, again having few contours especially towards the Gara's outlet, interpolation was performed by estimating distance from the nearest contours upstream and downstream and rounding down to allow for slight concavity. The Gara also enters a marshy area before emptying into Slapton Ley itself, and this former tract was included in the matrix, although it is devoid of contours for guidance on the map. Reference had to be made in this case to documentation on the area , where it is recorded that the surface of the Ley at Slapton Bridge stands at an average height of 10 feet OD (Mercer, 1966). The marshy area was therefore taken to be at that height also.

The important thing is to carry on with the job bearing in mind that great accuracy is not going to be possible anyway given the contour interval and contour accuracy of the map information. Evans sums up this attitude well : 'time is not spent agonizing over the last metre or two, or taking precise distance measurements. Errors of a few metres are unavoidable, and occasional larger errors will occur due to irregularities between

contours' (ibid). In view of all this a 50 m mesh was definitely the finest resolution that the map data would support, and although the altitude matrix data were recorded to the nearest 2 feet (rounding up if half-way between), their true accuracy is likely to be no more than to the nearest 6 feet (D.W. Rhind, personal communication). This is because the requirement for contours on Ordnance Survey maps is that they have standard errors smaller than one quarter of the contour interval (Harley, 1975), which was 25 feet on this map. Numerous field workers have in fact testified to the high quality of OS maps (e.g. Clayton, 1953), as did this study in the previous chapter. The extra precision in recording heights to the nearest 2 feet here may appear spurious, but avoidance of excessive rounding is helpful to algorithms threading a slope path through matrix information (chapter 4).

A major problem with the manual method was the extreme tedium of the task of recording heights : work on the Gara took 15 days. On the positive side, the geomorphologist will at least know his or her study area fairly intimately after this amount of close scrutiny!

3.4 Construction of an altitude matrix of Netherhearth catchment by digitising contours and interpolation using GPCP

Digitising the 94 contours on the map of the catchment took most of three days using the Summagraphics Digitiser in point mode (stream mode was found to generate too many coordinates, even when set to minimum speed). The files of coordinates were then edited into a form usable by GPCP.

The General Purpose Contouring Program, written in FORTRAN by Calcomp (see Calcomp, 1973, 1974), will accept gridded or irregularly-spaced control (input) data, from which it constructs and plots contours by interpolation. If irregularly-spaced control data such as

digitised contours are input, GPCP interpolates heights on a grid pattern at a grid mesh specified by the user, before proceeding to the contouring stage using this grid information; it is possible, using the 'PNCH' option of the program, to obtain a listing of this matrix. This is the part of the package which is of most use to a project concerned with altitude matrices - although contour plots were also generated to provide an important visual check on the quality of the interpolation by comparing them with the original map. A grid mesh size of 10 m was chosen as being the most detailed that a map at 2 m contour interval of this fairly gentle topography could support. The grid mesh heights output are expressed to three decimal places, this unwarranted precision being retained for the same reasons as were stated in the previous section for the Gara matrix.

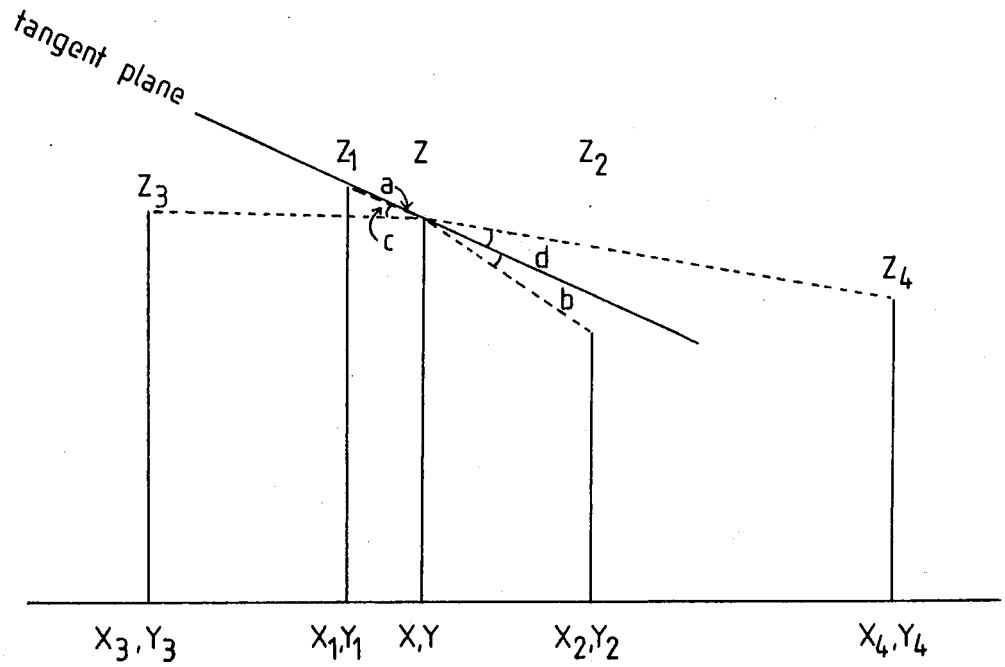
Taking each input control point in turn, GPCP calculates the gradient of the ground at that point (call its horizontal coordinates (X,Y) - see figure 3.1) by examining the Z (height) values of (X,Y)'s nearest n control points and constructing a tangent plane at (X,Y) constrained to pass through (X,Y)'s Z value. (n can be specified by the user, and is an important source of flexibility in the program, discussed below). The plane must minimize the angles it makes with lines joining (X,Y)'s Z value to the Z values of (X,Y)'s n neighbours, illustrated in figure 3.1. Clearly, a near neighbour should have more influence on gradient determination at a control point than the furthest away of the n, so that a weighting function is applied to each control point's influence on (X,Y)'s gradient, of the form

$$W = (R_j / R_{n-1})^2 \qquad \text{equation 3.1}$$

where

R_j is distance from (X,Y) to (X_j,Y_j) for j=1,2,3,...,n

R_n is radius of neighbourhood



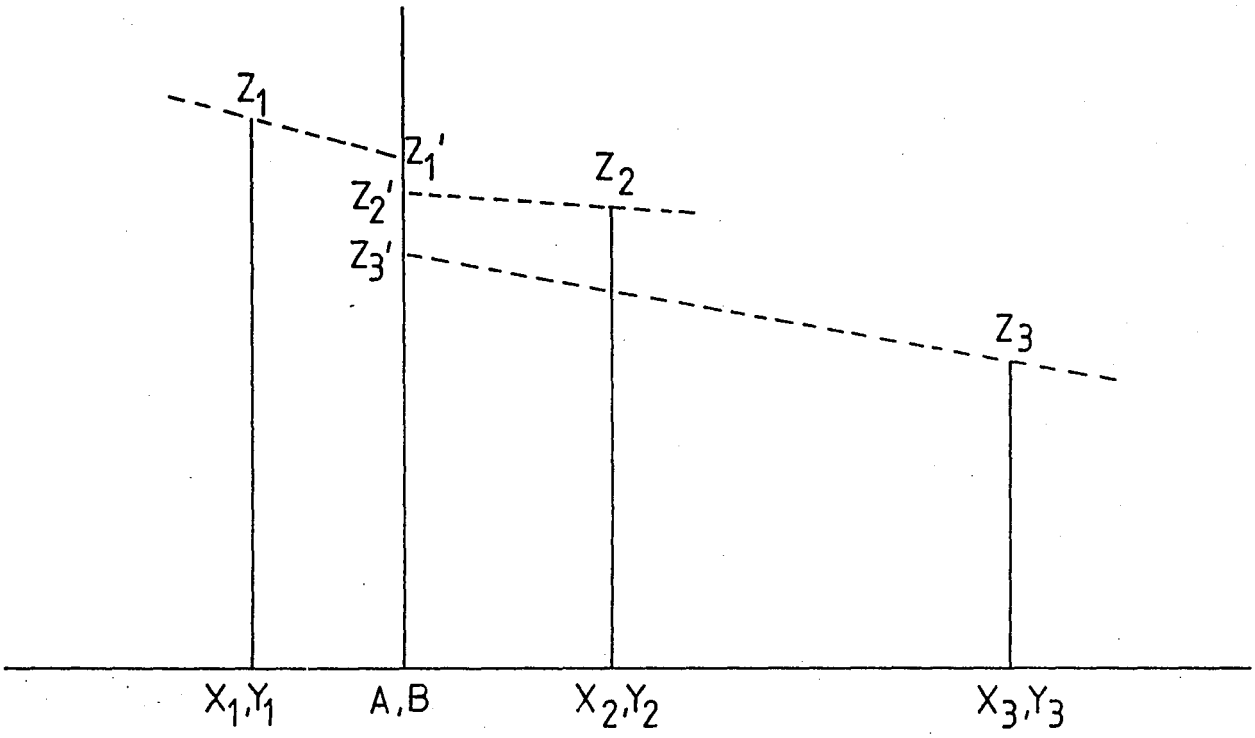
(X,Y) is control point, height Z, whose gradient is being determined. ($X_{1,\ldots,4}$, $Y_{1,\ldots,4}$), with heights $Z_{1,\ldots,4}$, are (X,Y)'s four nearest neighbouring control points, portrayed for simplicity as though all five points lie in the same vertical plane.
The tangent plane is constructed such that it minimizes the angles (a,b,c and d) it makes with lines joining (X,Y,Z) to ($X_{1,\ldots,4}$, $Y_{1,\ldots,4}$; $Z_{1,\ldots,4}$), according to the weighting function (equation 3.1, see text), such that nearer points exert greater influence : here, angle a's influence is greater than that of angle d.

Figure 3.1 : Gradient determination by GPCP.

When each control point has a gradient associated with it, a second series of operations is performed. Each desired grid point (call it (A,B) - see figure 3.2) is taken in turn and the gradients (as determined above) of its m neighbouring control points are examined. m can be different to n above - and is again specifiable by the user. The tangent plane specifying the gradient of each control point is extended to where it meets a line vertically above (A,B). The value of Z (height) to be assigned to grid point (A,B) is determined from the Z values that (A,B)'s m neighbours' gradients would predict by again weighting their influence by applying the function set out above (equation 3.1).

Experimentation was carried out with different values for n and m, comparing contour plots produced by GPCP with the original map, and an optimal value of n=m=20 was decided on (figure 3.4). The default n=m=8 was found to give a surface with numerous localized swellings and depressions, as can be seen in figure 3.3, due to the absence of the smoothing effect of more distant neighbours' influence. n=m=20 still produced irregularities in flatter topography, where gradient information from each individual point is idiosyncratic, and for the areas where this was most pronounced the original input control information (digitised contours) was thinned by taking out every other point, so in effect making a neighbourhood size of n=m=40. However, for steeper areas (covering most of the map) it was felt that a value for n and m any larger than 20 would create too generalised a surface.

GPCP requires a considerable amount of CPU time and memory : the Netherhearth matrix of 150 x 235 points took 1364 CPU seconds on the IBM 370 at Newcastle. (As a comparison, the same machine took 150 CPU seconds to perform the steps in program 'G' - described in section 3.7 - on the final Netherhearth matrix). Control point information



A and B are the horizontal coordinates of a grid intersection whose height (Z value) is to be determined by GPCP·($X_{1,\ldots,3}$, $Y_{1,\ldots,3}$) are its three neighbouring control points, having heights Z_1, Z_2, Z_3. Each of these control points possesses a tangent plane (shown on this figure as dashed lines), fitted by the procedure illustrated in figure 3.1, and the heights at which these planes cross a vertical line at (A,B) are Z_1', Z_2', and Z_3'. (For simplicity this diagram shows a situation where all four points happen to lie in the same vertical plane). The Z-coordinate of (A,B) will be derived from $Z_{1,\ldots,3}'$ using the weighting function (equation 3.1, see text), such that Z_1' (predicted by the nearest control point) will have more influence than Z_3' (predicted by the furthest point).

Figure 3.2 : Grid point altitude determination by GPCP.

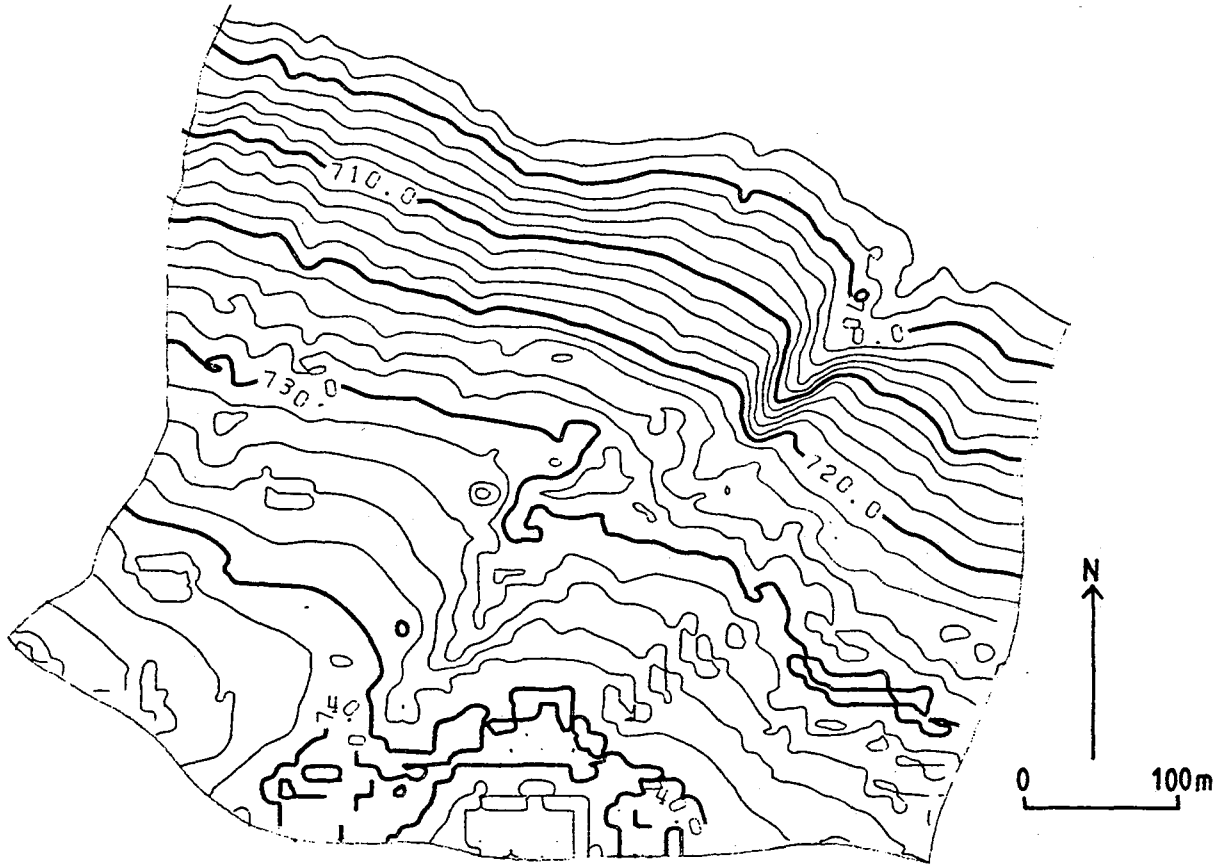


Figure 3.3 : Contours on southernmost part of Netherhearth catchment produced by GPCP from a matrix interpolated by it using search parameters n=m=8.

This matrix was judged to be successful and was retained. The 740 m digitized contour in the very south of the catchment had been thinned to half the original number of points before input to GPCP in order to give a smoother resulting contour in this low-gradient area.

Figure 3.4 : Contours on southernmost part of Netherhearth catchment produced by GPCP from a matrix interpolated by it using search parameters n = m = 20.

for GPCP had to be input in four separate batches and the resulting matrices later fitted together to make the final one. However, once the user has acquired competence in its use, this package is a very valuable asset.

The last stage in the production of the matrix was the discarding of matrix points outside the catchment's watershed, as GPCP produces a matrix only within rectangular, rather than irregularly-shaped, areas. This can be performed on the computer using a standard point-in-polygon program (e.g. see Baxter, 1976; Kiossev, 1981; Deimel Jr et al, 1982).

3.5 Construction of an altitude matrix by levelling, within the catchment of Netherhearth Sike

The area of the catchment marked by the square ABCD on figure 3.5 was chosen for survey, having varied topography incorporating gently-sloping shoulder, more steeply-sloping Netherhearth valley side, main channel, and tributary gullies flanked by peat cliffs.

The first operation of the survey was to establish a temporary bench mark (TBM) within the matrix area; choice was limited in this wet, peaty ground to a place by the main stream where a large flat rock appeared at the surface. Levelling operations using a Kern GK1-A quickset level proceeded from here to the southern corner ('A' - see figure 3.6) of the matrix, which was marked with a stake driven into the ground and then defined as follows. The level was positioned with plumb-bob directly over the stake and pointed straight across the valley in the direction chosen for the western corner ('B'); a ranging pole aligned with the level's vertical cross-hair was driven into the ground here ('E' on figure 3.6). Thence the level was rotated through 90° to face in the direction of the eastern corner (D) and the same procedure carried out (placing a ranging pole at F). The level was

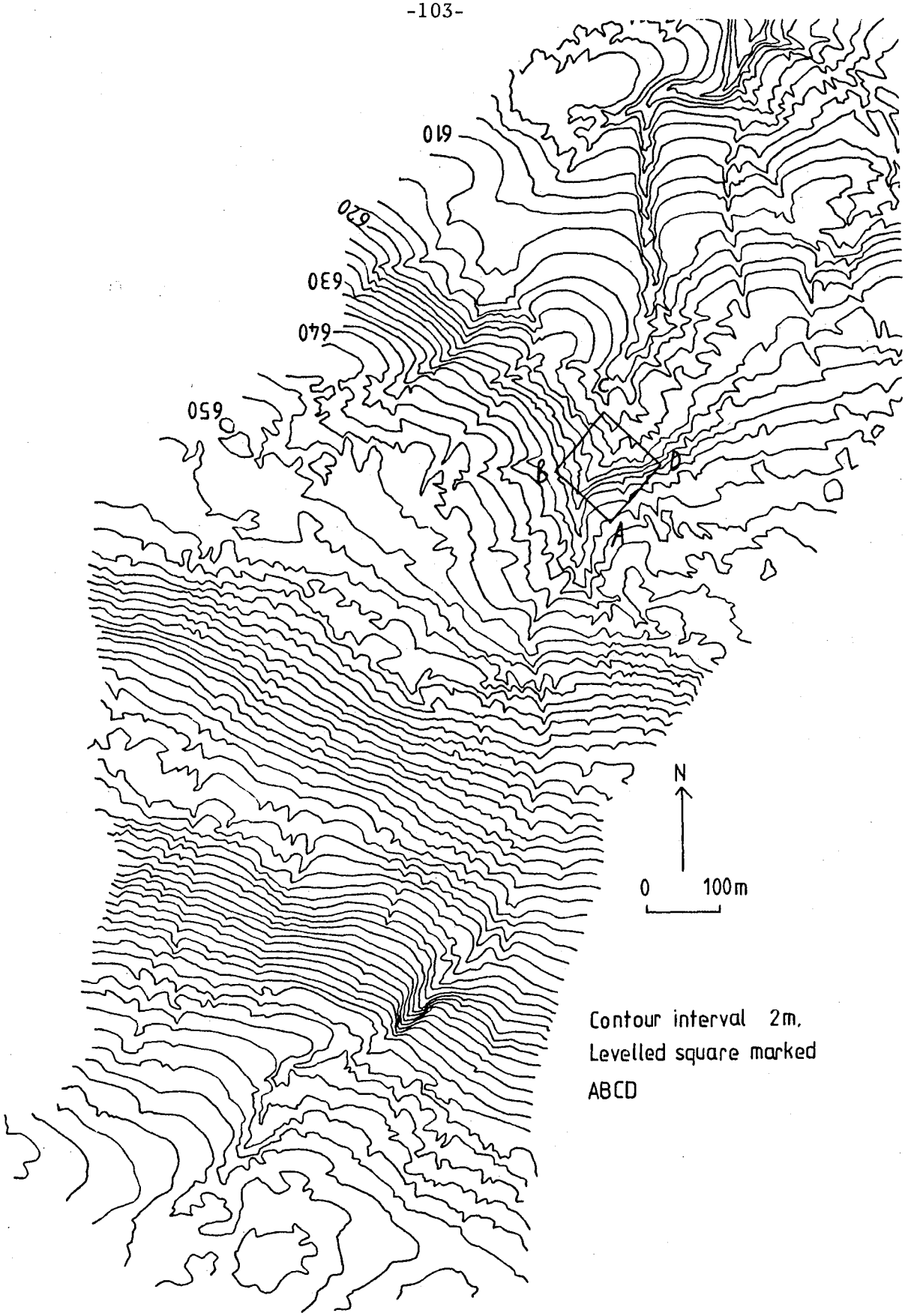


Figure 3.5 : Map showing position of levelled matrix in Netherhearth catchment. Contours (2 m interval) from the original photogrammetric map by M. Evans.

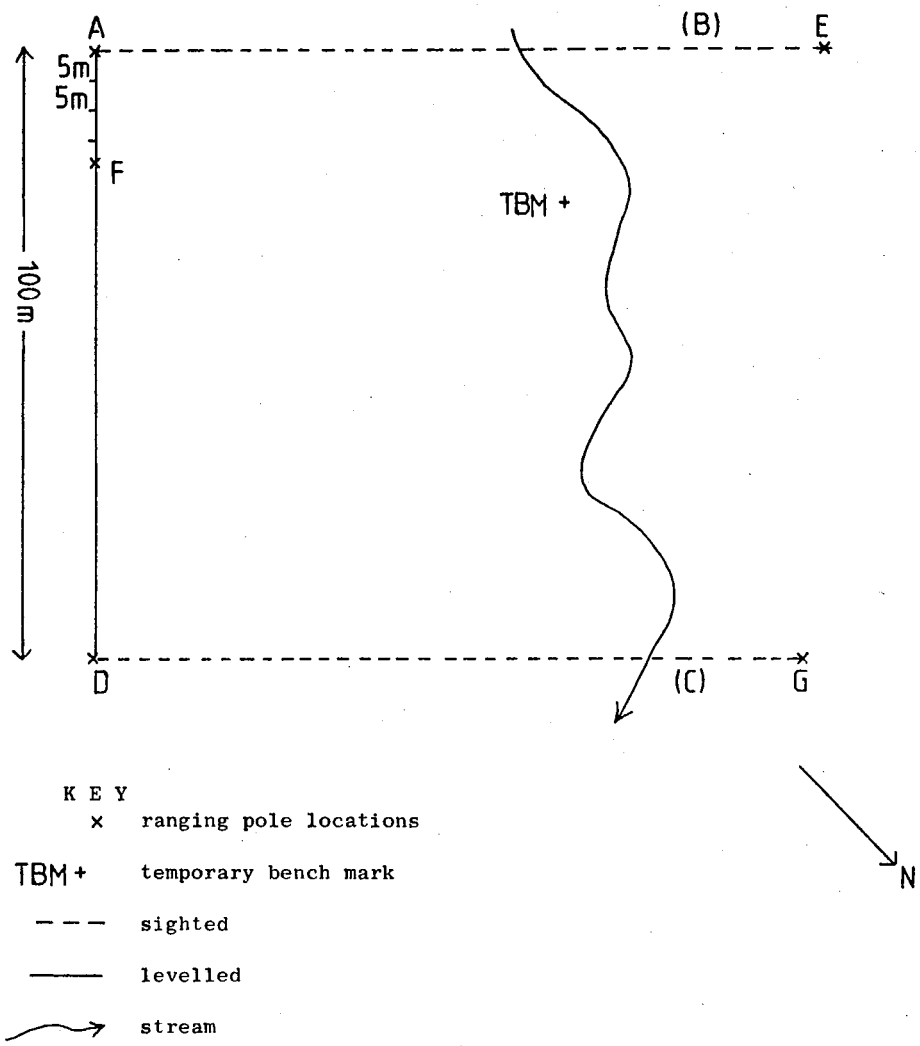


Figure 3.6 : The framework of the levelling survey.

then moved and a ranging pole inserted where the stake had been, at A.

Next a straight traverse was levelled from A to D, straightness being ensured by visual checks to see if new ranging poles being inserted were aligned with those at A and F. This operation could have been made more reliable by using a theodolite to span the traverse (although some ground would still have been hidden by topographic hollows and rises), but it was important to keep to a minimum the amount of equipment carried each day between field station and surveying site. At 5 m horizontal intervals measured along the traverse by stretching a metal tape taut and horizontal, heights were determined by levelling onto the staff. Distance estimation by tacheometry had been attempted initially, using the stadia hairs of the level and instructing the 'staff man' to move until a 5 m distance was indicated by the reading, but this proved time-consuming and inaccurate in the persistent high wind of this Pennine catchment, which made it difficult to hold the staff still and vertical for any length of time. Heights were determined at 5 m horizontal intervals along the traverses even though the final matrix was to be at 10 m mesh, to act as a check on the latter and indicate whether any more detailed scale of ground surface configuration was being filtered out by choice of 10 m mesh, bearing in mind the BGRG's recommendation for field survey with ground surface lengths of 5 m (see chapter 2). Figure 3.7 shows that use of a 10 m interval smooths the form of some of the gullies recorded with 5 m lengths, although - importantly - it does not filter them out altogether.

D having been determined by the traverse, the level was set up over D and a right angle defined for this corner (placing a ranging pole at G), as it had been for the southern corner at A. Thus base-line AD, and two right-angles off it at A and D respectively, had been determined in accordance with the surveyor's principle of working from the

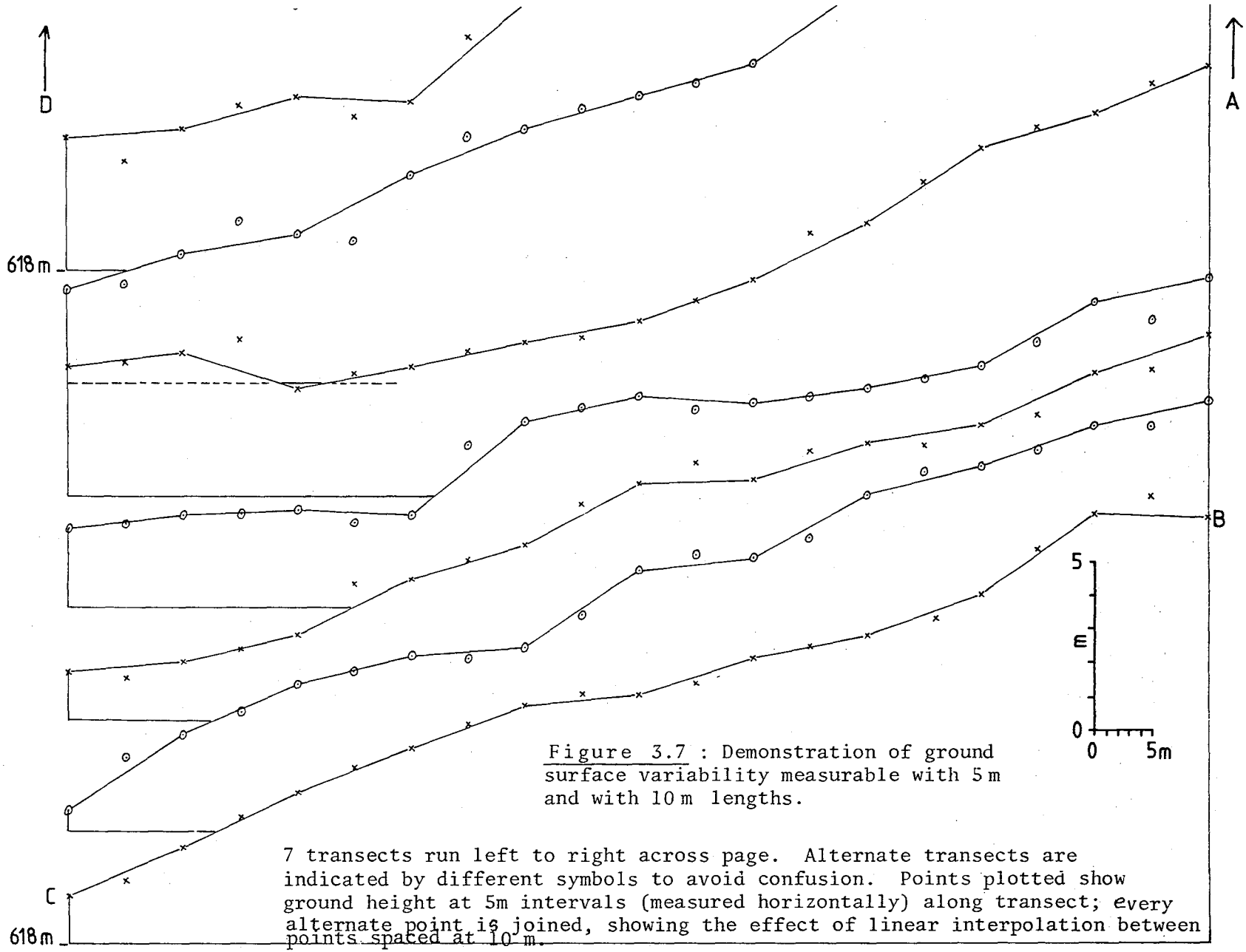


Figure 3.7 : Demonstration of ground surface variability measurable with 5 m and with 10 m lengths.

7 transects run left to right across page. Alternate transects are indicated by different symbols to avoid confusion. Points plotted show ground height at 5m intervals (measured horizontally) along transect; every alternate point is joined, showing the effect of linear interpolation between points spaced at 10 m.

whole (the accurately-defined framework) to the part (details for which precision is less critical as accuracy of whole survey does not depend on them), the set-up illustrated in figure 3.6.

A nylon rope 100 m long was knotted at 5 m intervals and used pulled taut and as horizontal as possible for distance measurements in all further traverses. Some accuracy was lost this way, as it was not possible to stretch the rope exactly horizontally along its 100 m length to define measurement stations; however it saved a lot of time . As it was, the survey took two adults and a boy four days' work, during which the interest of the helpers inevitably flagged.

The rope was stretched taut and semi-horizontal along each of the nine inner traverses and BC in turn, staff readings being taken with the level at 5 m intervals along each traverse. Finally, the stretch from C to the TBM was levelled so that closure error could be calculated. This worked out at 0.204 m, which is more than seven times the limit acceptable for ordinary levelling quoted in Bannister and Raymond (1977, 102) as $\pm 25\sqrt{K}$ mm, where K is the length of circuit covered in kilometres. However this survey did have to cope with severe difficulties : many backsights and foresights were needed on account of the hummocky terrain (peat haggs), boggy ground made it difficult to keep the staff in position while changing from foresight to backsight, plus wind and rain. The error was distributed evenly among the height values in applying the correction to produce an altitude matrix from the data.

The absolute heights of the matrix points surveyed could have been determined by levelling from the TBM to the Ordnance Survey's nearest bench mark. However, since the latter was 4½ km away, and relative rather than absolute height information was required, the height at TBM was only estimated (as 627.0 m) from the map and the

rest of the heights calculated from their relation to TBM established in the levelling.

3.6 Construction of a matrix of the levelled square, using GPCP

First, the exact area levelled in the survey described in the previous section had to be demarcated on the photogrammetric map of Netherhearth Sike catchment. This involved some compromise, probably because the exact configuration of land and channel had changed between the flights for the map made in June 1969 and the field survey in September 1981. The area on the map settled upon had the stream outflow in the same place, TBM the same side of the stream,but inflow slightly 'out' compared with those positions in the levelled matrix. The altitudes at its corners were respectively 0, 1.5, and 1 m too high, and 0.9 m too low.

The corners of this exact square on the map were then digitised, and the angle between the square thus defined and the coordinate directions used in digitising the contours (as described in section 3.4) was calculated. The coordinate system in which the digitised contour points were expressed was then rotated through this angle using a small computer program, because GPCP can only create a matrix 'square on'. Then GPCP was run on this rotated control information to create a matrix of the same area at 10 m mesh, with search parameters n=m=20 as before.

The median of the differences in height for equivalent points in the levelled and GPCP-made matrices was found and added to each height in the levelled matrix so that relative rather than (unimportant) absolute differences in the methods of measuring the same land could be highlighted. The comparison is made in section 3.8, after a brief description of program 'G', which is to be used in this comparison.

3.7 Program 'G'

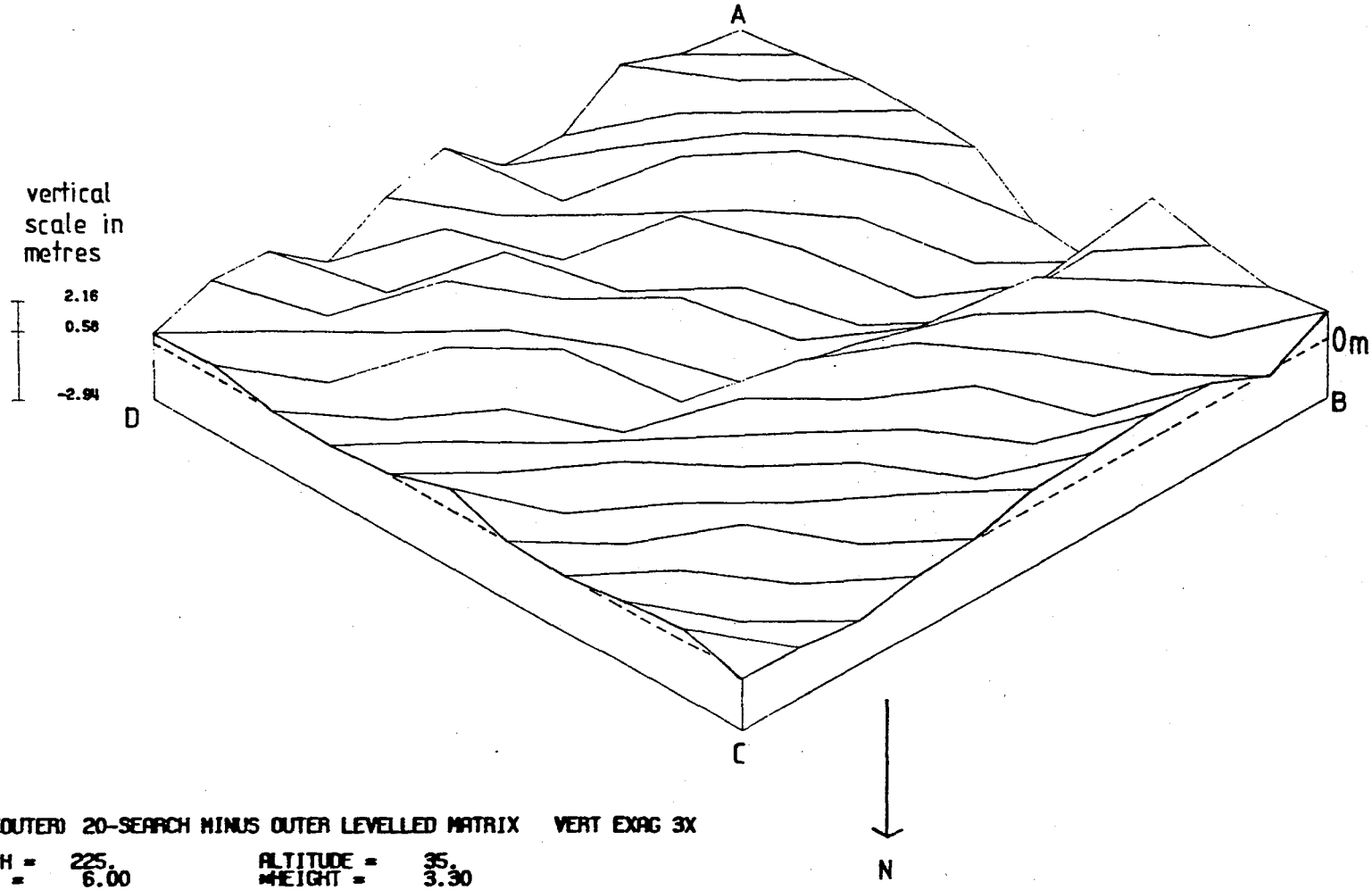
For every grid intersection (vertex) of the matrix, G fits a quadratic surface by least squares to it and its eight neighbouring vertices. Then for the central vertex of the nine, the program calculates altitude (not quite the same as the input altitudes usually because the quadratic surface is not constrained to pass through the points it is fitted to), gradient and aspect (first vertical and horizontal derivatives of the surface respectively) and profile and plan curvature (second vertical and horizontal derivatives, in degrees per 100 m). The convention for quantifying curvature, employed here, is that convexity is expressed as a positive figure, and concavity negative.

The resulting frequency distributions of the five attributes of land surface form listed above are presented as histograms by the program and also summarized using moment-based measures (mean, standard deviation, skewness, kurtosis). The spatial distributions of land form values are shown by line printer maps, and relationships between them by scatter plots and calculation of correlation coefficients.

Detail on the thinking behind the program is available in Evans (1979; also 1980, 1981); the derivation of the equations used is explained in Young (1978).

3.8 Comparison of levelled and GPCP-made matrices for the same area

The 'topography' of error created by subtracting the levelled matrix from the GPCP-made one is shown in figure 3.8, a plot produced by use of Harvard University's 'SYMVU' (Muxworthy, 1972) available as a package on the IBM at Newcastle. The most noticeable thing about this 'topography' is that GPCP has made the valley too deep, presumably because there was not enough control information (digitised contours) in the valley floor area to indicate a flat-floored valley rather



GPCP (OUTER) 20-SEARCH MINUS OUTER LEVELLED MATRIX VERT EXAG 3X

AZIMUTH = 225. ALTITUDE = 35.
*WIDTH = 6.00 *HEIGHT = 3.30

* BEFORE FORESHORTENING MAR 11, 1982

Figure 3.8 : 'Topography of error' : GPCP matrix compared with that levelled in the Netherhearth.

than a plunging one. Figure 3.8 shows that the maximum error is 3 m, which is not excessive.

Table 3.2 displays summary statistics for the land form attributes estimated by G for the GPCP and levelled matrices. It shows that the figures for mean and standard deviation of altitude and gradient are very similar for the two matrices, which is encouraging. The curvature figures are less comparable however : too much attention should not be paid to the mean of profile and plan curvature figures as these are liable to fluctuate around zero according to the lengths of the tails of the distributions, and are not too interesting anyway; the differences of 35 and 15% respectively in standard deviations are important however. Predictably the field-measured matrix displays the greater variability in curvature in both cases, and these differences are indicative of the generalization of the topography that has taken place in the production of the map and then interpolation by GPCP. It would have been more disturbing if the GPCP figures had been greater than the field's, as this would have indicated that GPCP was creating artificial bumpiness, as was illustrated for the n=m=8 case in figure 3.3. It must also be borne in mind that there were errors in the field survey, which could have introduced artificial bumpiness.

It has already been noted (chapter 2) that the Netherhearth catchment has rugged small-scale relief features in the form of numerous peat flushes (figure 2.15) and minor channels flanked by peat haggs : these have probably been responsible for introducing more variability in field-measured profile curvature than in field-measured plan curvature, when compared with the GPCP-generated. The standard deviation of profile curvature from the field-levelled matrix is very similar to that estimated from field profiles in the Netherhearth when interpolated to 5 m horizontal constant lengths (table 2.3). This implies that some fieldwork

Table 3.2 : Comparison of summary statistics of land form attributes for the two matrices covering 100 m x 100 m of Netherhearth Catchment

		Matrix made by levelling	Matrix made by GPCP on dig. contours	Difference between the two, expressed as %, i.e. $\frac{\text{levelled-GPCP}}{\text{levelled}} \times 100$
Altitude in metres	mean	626.85	626.82	0
	st.dev.	4.17	4.00	4.08
	skew*	0.34	0.35	- 2.94
	max.	636.05	635.42	.10
	min.	619.91	620.12	- .03
Gradient in degrees	mean	9.62	9.26	3.74
	st.dev.	3.77	3.84	- 1.86
	skew*	0.53	0.52	1.89
	max	18.51	17.86	3.51
	min.	2.77	2.05	25.99
Profile curvature in degrees/100 m	mean	- 3.58	- 7.00	95.53
	st.dev.	52.90	34.26	35.24
	skew*	- 0.46	0.04	-108.70
	max.	110.65	86.08	22.21
	min.	-170.37	-88.76	- 47.90
Plan curvature in degrees/100 m	mean	- 63.29	-122.17	93.03
	st.dev.	477.89	406.83	14.87
	skew*	- 0.85	- 1.84	116.47
	max.	1088.52	587.55	46.02
	min.	-1580.63	-1508.16	- 4.58

* Skewness is dimensionless

is necessary to estimate this parameter accurately, although a profile survey would be more efficient than the time-consuming field matrix survey.

3.9 Overview of matrix construction methods

For the matrices made from map information, the manual one (Gara catchment) is definitely most true to that map information - because GPCP is less reliable in certain areas, as was illustrated for the valley floor portion of the levelled square in Netherhearth. It is very difficult to mimic with a computer the seemingly simple decision-making of the manual encoder, because what a person can take in with a careful look at surrounding contours and a knowledge of landscape (described in section 3.3) requires a very sophisticated algorithm, which is expensive in terms of time and memory on a computer. Therefore computer interpolation seems a long way from being as accurate as manual for the same resolution of basemap, although computers have the advantage of being consistent and not prone to errors, unlike a bored operator. However, it is not true to say that the matrix made of the Gara catchment is therefore the most accurate because the map information was at a coarse resolution relative to the Netherhearth's, and had not been derived photogrammetically.

Interpolation using GPCP is accurate for areas of steady slope - such as the upper parts of the Netherhearth catchment - but encounters problems in dealing with sparse contour information in flatter areas, such as that catchment's southernmost headwater (note the thinning of control point information necessary, stated on figure 3.4). n and m (which specify search radii for GPCP interpolation routines), and the density of input control points, can however be varied with successful results, as this study has shown. If presented with a map with wide enough contour spacing to be easily digitised, and not too many flat or

irregular areas, this option would have much to recommend it in matrix construction.

As regards matrix-making by field levelling, this survey was complicated by choice of a particularly tough study area climatically; however if field survey of data for a matrix is required, the advice in the literature (e.g. Howes, 1977) favours survey of an irregular net of points at breaks of slope, summits, valley floors, and other surface-specific locations of importance, from which subsequent interpolation can create a grid pattern of points. Survey on a grid, according to Allan, Hollwey and Maynes 'has the disadvantage of being very wasteful of surveying time' (1968, 12), because the identification of the grid pattern itself is time-consuming. The accuracy of levelling instruments was largely wasted in this area due to the boggy ground and bad weather : the technique is too inflexible to be able to cope adequately with such conditions, and the result is hardly worthy of the time taken in surveying. More accurate information on the topographic attributes required in this research could be obtained for less effort by making the matrix as described above using GPCP, and taking slope profiles in the field as a ground truth check, particularly for curvature values. The positioning of these profiles so as to achieve optimum sampling coverage of the whole drainage basin, is the subject of investigation in chapters later in the thesis.

3.10 Gara and Netherhearth matrices analysed with 'G' : evidence on the influence of scale

An important advantage of altitude matrices is their constant horizontal grid mesh which means that their recording interval (resolution) is readily quantifiable, in contrast to surface-specific DTM's (see discussion, chapter 1) for which spacing between points is variable. Other studies with altitude matrices have noted the effect of grid mesh

on land form attribute values obtained (e.g. Evans, 1979; Gill, 1982; and other authors whose work is described in section 1.3), which is analogous to the influence of slope profile ground surface length noted in the literature and demonstrated for this study in chapter 2. Since the Gara matrix was made at 50 m mesh and the Netherhearth at 10 m, it is important to determine how much of the difference between land form attribute values yielded by them (table 3.3 rows 1 and 4) is due to scale of measurement, and how much to real and measurable differences in topography between the two areas.

The first three columns of table 3.3 show that altitude statistics are relatively resistant to the effects of altering grid mesh size, which is predictable. Columns 4 and 5 show that mean and standard deviation of gradient decrease steadily with increasing mesh; it is interesting that the decline is steeper for the Gara meshes investigated than for the Netherhearth, the latter's mean gradient declining by only .17° between 50 and 100 m meshes, whereas the effect of the same alteration of mesh in the Gara is to decrease mean gradient by 1.0°. This is probably because the steep valley sides of the Gara River are being progressively generalized at larger mesh sizes (100 and 150 m), whereas in the case of the Netherhearth the extremely short Sike valley sides are considerably smoothed at even a 10 m mesh (indicated by the fact that mean and standard deviation of gradient measured in the field with 1.52 m ground surface lengths were 7.64° and 6.07° respectively, compared with 5.95° and 3.10° for the matrix at 10 m mesh). With a 50 or 100 m mesh matrix in Netherhearth catchment one is simply sampling the regional slope of the catchment towards its outlet in the north, which is fairly uniform over large distances (signified by the low standard deviation of gradient by comparison with the Gara's at the same mesh), and resistant to the scale of measurement.

Table 3.3 : Summary statistics of land form attributes calculated by 'G' for the Gara and Netherhearth matrices processed at various grid mesh sizes

	ALTITUDE (m)			GRADIENT (°)			PROFC(°/100m)		PLANC (°/100m)	
	mean	st.dev.	skew	mean	st.dev.	skew	st.dev.	skew	st.dev.	no. of values
GARA										
(1) 50 m mesh	120.59	39.60	-0.40	7.40	4.55	1.16	9.62	-1.87	158.12	11525
(2) 100 m mesh	118.78	39.06	-0.36	6.40	3.53	1.17	5.91	-1.53	139.89	2711
(3) 150 m mesh	117.52	38.15	-0.33	5.36	2.84	1.21	3.65	-1.36	85.59	1151
NETHERHEARTH										
(4) 10 m mesh	645.21	49.77	0.49	5.95	3.10	0.64	28.32	-0.68	596.27	13327
(5) 20 m mesh	645.16	49.17	0.50	5.62	2.65	0.49	13.31	-1.01	485.10	3139
(6) 30 m mesh	645.35	48.47	0.51	5.43	2.44	0.51	7.59	-0.46	484.69	1307
(7) 40 m mesh	645.54	48.03	0.51	5.35	2.32	0.50	5.66	-0.50	279.02	696
(8) 50 m mesh	645.41	47.11	0.53	5.32	2.21	0.49	4.54	-0.16	87.04	415
(9) 100 m mesh	643.06	43.30	0.63	5.15	1.75	0.69	1.94	-0.08	27.71	71

Although the Gara catchment has greater mean gradient than the Netherhearth at 50 m mesh, the difference has narrowed by 100 m mesh, and, one would guess, would narrow again for 150 m mesh - although the small area of the Netherhearth catchment made it meaningless to take analysis of it to this level. The lessening of gradient in the Gara with increasing mesh size is illustrated visually in figures 3.9 and 3.10 for 100 and 150 m meshes respectively : the area of steep (10 - 20°) slope defining the main valleysides has markedly decreased on figure 3.10, and a predominance of 2 - 5° slopes away from the main valley takes over from the finer interdigitation of 2 - 5 and 5 - 10° slopes on figure 3.9 recording the presence of tributary valleys. The greater positive skewness of gradient in all cases for the Gara than for the Netherhearth supports the interpretation of a tail of high gradients along the main streams compared with the Netherhearth gradients which are more symmetrically distributed about the regional slope mean.

The decrease in standard deviation of gradient with increase in grid mesh size, clearly seen in table 3.3 for both Gara and Netherhearth matrices, accords with the finding of Carr et al that 'there is a pronounced tendency for the slope distributions to become more peaked, or grouped about a central class value, as map scale becomes smaller' (1963, 54).

Columns 7 and 9 demonstrate the sensitivity of curvature variability to mesh size. Both indicate the dangers of comparing statistics from different areas if the resolutions of the source matrices are not the same. Thus the Netherhearth at 10 m grid has a standard deviation of profile curvature three times that of the Gara at 50 m mesh, but when the former is processed at 50 m resolution also it gives a figure for this parameter smaller than the Gara's at 100 m. It is likely that at small mesh sizes, such as 10 m, the Netherhearth

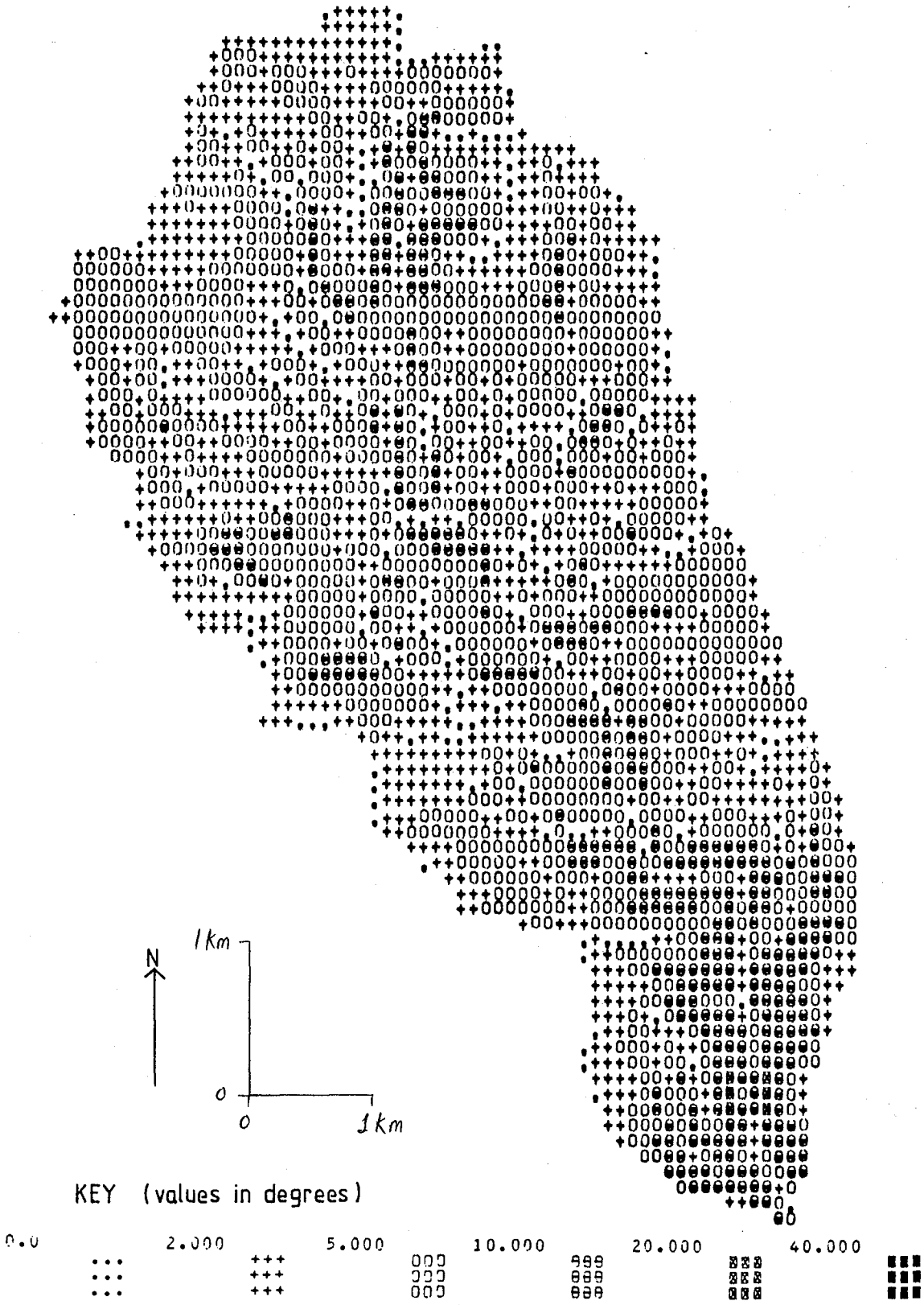


Figure 3.9 :- Map of gradient from Gara matrix at 100 m mesh (fixed class intervals).

K E Y
See figure 3.9

Figure 3.10 : Map of gradient from Gara matrix at 150 m mesh (fixed class intervals).

does display greater curvatures than the Gara would at that resolution, due to the deep incision on a detailed scale by channels in the former catchment : unfortunately data for the Gara in matrix form at such a resolution are not available.

The decline of standard deviation of plan curvature with increasing mesh size is discontinuous : for the Netherhearth, the figure declines sharply between 10 and 20 m meshes but is kept fairly constant to 30 m before declining again for 40 and 50 m meshes. These figures need to be treated with some caution as the distribution of plan curvature values is highly non-normal in all cases here; they suggest however that there are discrete scales of curvature in the catchment rather than a continuum. For a process study such a finding could be important, as some scales of this attribute would be likely to be more relevant to prediction than others. The same phenomenon is apparent in the Gara figures, where the decline in standard deviation of plan curvature is much smaller between 50 and 100 m meshes than between 100 and 150 m.

The conclusions to be drawn from this analysis of statistics of land form attributes for two very different catchments are that the grid mesh of the matrix does have an influence on land form attribute values, but that the precise nature of this influence depends on the topography of the catchment studied. This is illustrated by the fact that an increase in mesh spacing from 50 to 100 m in Gara and Netherhearth catchments produces a 13.5% decrease in mean gradient in the former case and only a 3.2% decrease in this parameter in the latter case. Nor are the attribute values obtainable from any one matrix a linear function of mesh size, as is illustrated by the decrease by 192°/100 m in plan curvature between mesh sizes 40 and 50 m for the Netherhearth, compared with a decrease of less than 1°/100 m between mesh sizes

20 and 30 m for the same matrix. The fact that an examination of the influence of scale brings these characteristics of the topography of the study area to light, is an argument for including such investigation in geomorphometric studies rather than simply regarding scale-dependence of results as a tiresome fact of life.

3.11 Conclusions and recommendations

For a geomorphologist wanting an altitude matrix to yield topographic information for a process study, the method of matrix construction would depend to a great extent on the level of land form detail required. For most 1:10,560 scale Ordnance Survey maps 50 m is the narrowest mesh that can be sanctioned; the same is true for the newer OS photogrammetric 1:10,000 scale maps with a contour interval of 10 m. For a matrix as detailed as the Netherhearth at 10 m mesh, a more detailed resolution of basemap than those universally-available OS scales would therefore have to be obtained. If such detail was required, the answer could be field survey : a grid pattern of control points need not necessarily be surveyed, as was emphasized earlier, since a grid could be interpolated later probably more efficiently. Photogrammetry would, however, be preferable.

Even for the 10 m field-surveyed Netherhearth matrix, the position of the stream could not be determined from the matrix altitudes alone : to record its exact course, supplementary field notes would have to be taken during survey, a conclusion also reached by Woodward (1979). This is part of the argument that the advocates of surface-specific DTM's charge against altitude matrices : that over much of a surface, a dense grid net is unnecessary to define topography adequately, but in some parts such as valley floors, detail is needed and may slip through the sampling net. A solution devised by some people involved in commercial

map production (e.g. Leberl and Olson, 1982) is to digitise drainage line and ridge elevation data, plus any other surface-specific information judged to be important, in addition to the grid of altitudes, and include them as control information input to the contour interpolation routines. A geomorphologist could do the same if he required a supplement to a matrix for accurate location of linear features. This principle could also be applied in the construction of the matrices themselves : thus as well as the digitised contour information input to GPCP in this study when making the Netherhearth matrix, the heights and locations of points along the streams (interpolated by the geomorphologist using his knowledge of the form of valley long-profiles) could be digitised and input to GPCP as extra control information. Such a course of action could have decreased the level of disagreement in the river valley between field-levelled and digitised-contour-derived matrices of the 100 m x 100 m Netherhearth square.

The results of comparing matrices at different meshes show that curvature statistics in particular are heavily dependent on grid mesh size, declining steeply for the Netherhearth as the mesh was increased from detailed scale (10 m) to more reconnaissance scale (50 m). Altitude statistics are more resilient, gradient statistics intermediate.

Comparison between land form attributes from field survey by profiling and from map-derived matrix will be made in chapter 5 for the Gara catchment, in which more complete coverage of the area by field profile survey was undertaken. The comparison between field and map-derived matrices for one small part of the Netherhearth described in this chapter has indicated a particular lack of comparability in standard deviation of profile curvature; this finding could be peculiar to the topography of the Netherhearth where channels in the peat may go undetected on a map but not in the field. Further investigation of the generality

of this finding is therefore necessary.

The alternative to field survey of a matrix, if detailed land form information is required, is to construct a matrix at the most detailed scale that map data will allow and supplement it by field profiling, the latter technique being more suited to the types of study area (boggy, remote) that geomorphologists often choose to study, than is precision surveying equipment. In the next chapter the construction of a computer program to thread profiles through matrices is detailed, in preparation for the derivation of a method to locate a few profiles according to stated land surface sampling aims on computer, profiles that it would then be possible to measure in the field. This program also permits many sampling experiments that would be almost inconceivable with field profiling.

3.12 : Notation

A,B — two perpendicular coordinate directions in the horizontal plane specifying position of a grid vertex interpolated by GPCP

j — a counter

K — horizontal length of circuit covered in a levelling survey, in km.

m — number of neighbouring control points whose gradients are used by GPCP to determine altitude of each interpolated grid vertex

n — number of neighbouring control points used by GPCP to determine gradient at each control point.

R — radial distance measurement employed in weighting function of GPCP

W — value of weighting function applied by GPCP in determining gradients of control points and heights of grid vertices

X,Y — two perpendicular coordinate directions in the horizontal plane specifying position of a control point

Z — vertical coordinate direction signifying altitude, in plane at right-angles to the horizontal plane.

Z' — a predicted Z value at a grid vertex, achieved by extension of the tangent plane of a neighbouring control point in GPCP.

CHAPTER 4 : PROFILES COMPUTED FROM MATRICES : THE PROGRAM SLOPROFIL.2

4.1 Introduction

4.2 A trial program : SLOPROFIL.1

4.3 SLOPROFIL.2 : a general outline

4.4 Subroutine JNJFIT

4.5 Preliminary validation of program SLOPROFIL.2

4.6 Concluding remarks

4.7 Notation

4.1 Introduction

In this chapter the construction of SLOPROFIL.2, a computer program in FORTRAN, is outlined and justified. The purpose of the program is to construct profiles, using altitude matrix data, which will be similar to those obtained by fieldwork.

The aims of this work are two-fold : firstly, to test the ability of altitude matrix data, obtained from maps as was described in the previous chapter, to generate realistic contour-orthogonal profiles. Once this has been demonstrated, the second aim is to evaluate the effects of varying profile sample sizes and sampling patterns on land form attribute data obtained from these computer-generated profiles. The first aim will be carried out in chapter 5, where field and matrix-derived profiles are compared; the second is dealt with in chapters 6,7 and 9, where data from matrices analysed with 'G' (as in sections 3.8 and 3.10 above) are compared with data from matrix-derived profiles produced by SLOPROFIL.2.

First, however, it is important to deal in some detail in the present chapter with the construction of the program SLOPROFIL.2, especially written for this research. This chapter aims to make the structure of the program and the model of terrain used by it as clear to the geomorphologist as - it was argued in chapter 2 - the field profiling procedure should be.

4.2 A trial program : SLOPROFIL.1

It is a fairly simple matter to trace a profile upslope from a grid intersection (vertex) to the one vertex out of its eight neighbours whose height exceeds it by the greatest amount - as illustrated in figure 4.1. One potential problem with this technique is that it is

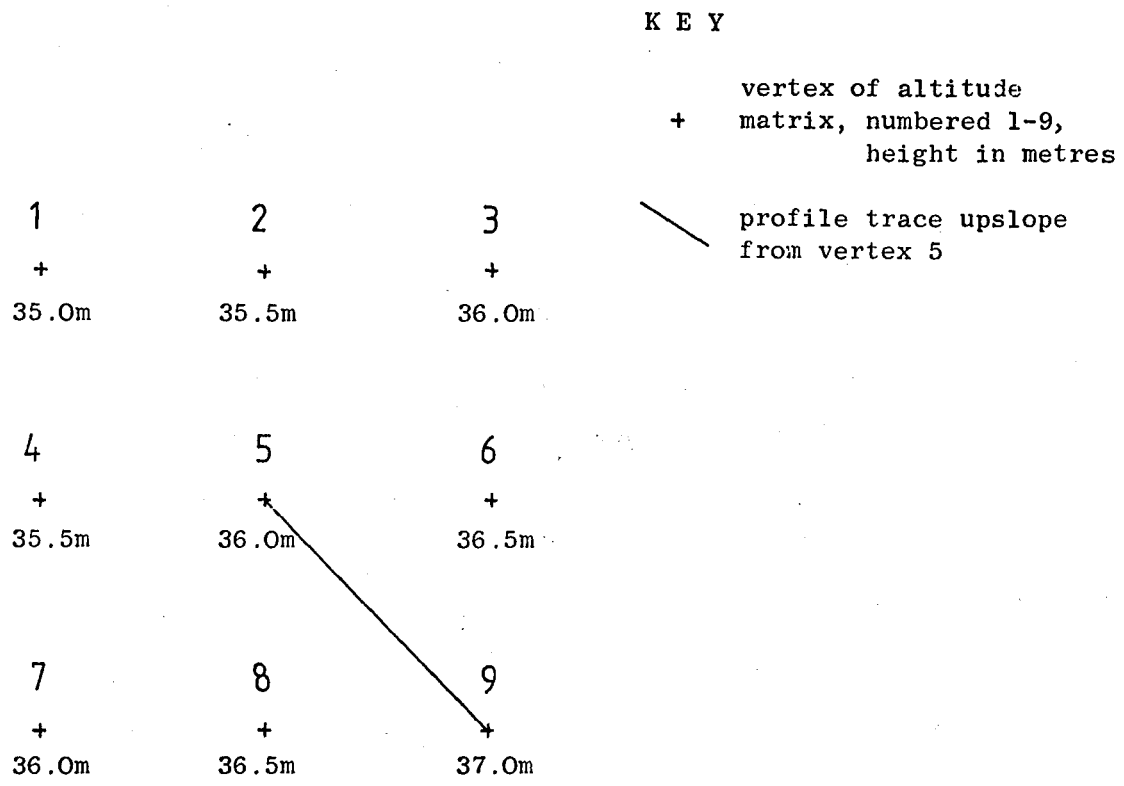
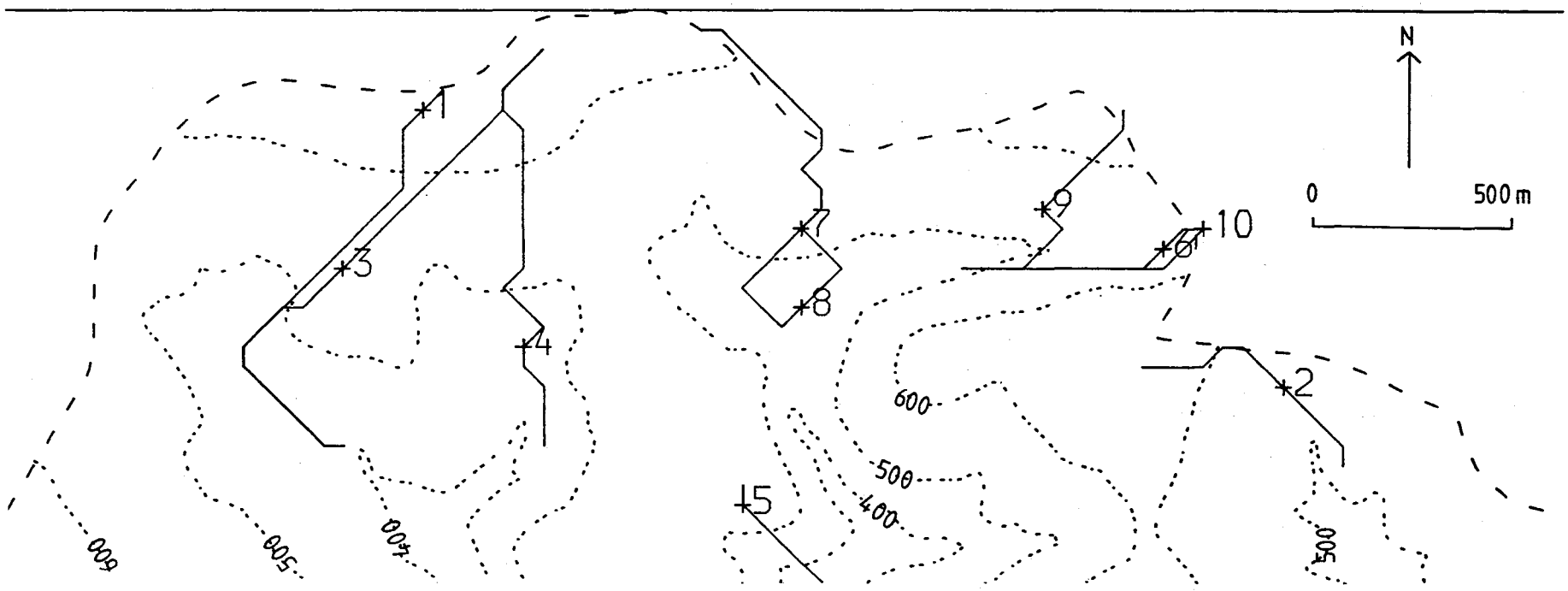


Figure 4.1 : Illustration of procedure when ascending a slope by following vertices of altitude matrix.

possible, with altitude data recorded to the nearest 0.5 m for example, that the trace could have a choice of two or more directions in which to ascend : this would have been the case for the situation depicted in figure 4.1 if the height of vertex 9 had also been 36.5 m . The Gara matrix heights were recorded to the nearest 2 feet, so this situation did indeed arise. There is a choice of solutions : one option is to proceed to the last (or first : the important thing is to be consistent) of the equal-greatest-altitude vertices to be scanned in a search from vertex 5 of its eight neighbours. The second and possibly better alternative would be first to smooth the data gently, thereby adding extra decimal places on the ends of altitudes such that two neighbours are very unlikely to be the same.

The greatest problem encountered was that profiles were bound to zig-zag totally unrealistically when the vertex-tracing program SLOPROFIL.1 was run on coarse-mesh matrix data, such as the 50 m grid of the Gara (figure 4.2). It has already been stressed in chapter 3 that 50 m mesh is often the most detailed that can be justified from 1:10,560 or 1:10,000 scale Ordnance Survey maps : this problem with vertex tracing could therefore only be solved by obtaining more detailed matrix data than is possible from commonly-available map scales. To do this would probably necessitate fieldwork or plotting from air photographs, either of which would add undesirable time, effort and cost to an exercise.

In the rest of this chapter, the construction of a program SLOPROFIL.2 to trace between vertices is detailed. There are those who argue (e.g. Collins, 1975) that interpolation between matrix vertices should be avoided as it is inevitably inaccurate, a mathematical generalization of the (unknown) real terrain between sampled points. The alternative has been shown here to be unacceptable for defining slope profiles however. SLOPROFIL.1 is not reproduced in this volume as it has



KEY

profile (point of origin indicated with a cross and numbered)

catchment watershed

contours (heights in feet)

Figure 4.2 : Slope profiles generated from 10 randomly-located vertices by SLOPROFIL.1 in the northern part of the Gara matrix at 50 m mesh.

been superseded by SLOPROFIL.2, which is vastly superior.

4.3 SLOPROFIL.2 : a general outline

SLOPROFIL.2 follows M. Young's FORTRAN program G (previously described in section 3.7; see also Young, 1978 and Evans, 1979) in fitting local quadratic surfaces to overlapping sets of 3 x 3 matrix vertex heights. The 'local' approach has much to recommend it : as Jancaitis and Junkins put it, 'Mathematical modelling of local surface geometry using locally valid surfaces has the inherent advantage that only local data need be processed; and the complexity of the mathematical model can be held to a reasonable level' (1973, 28). Quadratics fitted to 3 x 3 points keep neighbourhood size small 'so that the generalisation inherent in a grid-based approach is minimized', while 'the presence of three "spare" data points means that the local quadratic surface is overdetermined, and does not need to pass exactly through the nine data points. This makes some (small) allowance for rounding and other errors in the data' (Evans, 1979, 28).

The use of quadratics as local approximations to the ground surface is a satisfactory compromise between the fitting of linear surfaces, which would generalize the topographic variations out into a set of artificial linear planes, and the fitting of cubic or higher-order surfaces, which would require more data points per fit and so generalize a wider surface area as one mathematical function - as well as being more expensive in computation. It is not expected that quadratic surfaces provide perfect fits to all localities of an altitude matrix, and 'In reality, little is yet known about appropriate mathematical functions which adequately define real variables; only long experience can reveal the most suitable functions for particular variables' (Rhind, 1971, 156). Results from using quadratic surfaces in G have been

satisfactory however (Evans, 1979) and there are numerous other instances in the literature of quadratic surfaces being used in topographic modelling, for example by Chorley (1969), Struve (1977) and Allam (1978). Grant (1957) stated that for most geophysical data, the trend can be described adequately by a polymonial of low order, the main exception being when the data contain sharp discontinuities : for example seismic reflection time data across a fault. The majority of topography is free from such interruptions.

Fitting quadratics to neighbouring surfaces would not by itself guarantee smooth junctions along the numerous boundaries between local surfaces however, so that artificially stepped profiles would be generated. (This is not a problem in program G because only values at vertices are used). To ensure continuity of the surface across boundaries, a weighting function devised by Jancaitis and Junkins (op.cit.) is applied in SLOPROFIL.2 to overlapping quadratics : this guarantees continuity in value and in first partial derivatives across boundaries. Jancaitis and Junkins found that this degree of continuity was necessary and adequate to ensure smooth and continuous contour lines from digital terrain models (UNAMACE data) possessing considerable background noise due to the method of encoding. It was considered that first-order continuity would also be adequate in SLOPROFIL.2 to define contour orthogonals. The application of the weighting function to this particular problem, and its detailed properties, are set out in section 4.4 below on SLOPROFIL.2's subroutine JNJFIT.

In SLOPROFIL.2, points of origin for profiles may be generated by the program either as random vertices, or as a grid pattern of vertices at mesh spacing chosen by the user, or input as a series of coordinates (which need not be vertices). From a point of origin, the trace is defined by the following steps :

1) initial upslope advance, by determining the direction in which the rate of change of height with horizontal distance of the (weighted) local surface at the point of origin is maximized, and advancing a pre-defined horizontal distance along the bearing defined by the corresponding horizontal derivative (aspect). Distance is controlled by variable STEPLN, input by the user - it could be set to 5 m for example, for comparability with that recommended by Young (1974) for use in the field.

(Derivatives are used to ensure orthogonality to contours : a solution based on tracing to the highest point around the edge of a 2 x 2 vertex matrix square, for example, would have caused results to be an artefact of positioning of grid lines).

2) initial downslope advance, by moving STEPLN units along a bearing at 180° to that in (1), which is the direction in which the rate of change of height with horizontal distance is most negative from the point of origin.

3) second upslope step, achieved by finding the direction of maximum slope at the point defined in (1), and advancing STEPLN units along the bearing thus defined.

4) second downslope step, achieved by finding the direction of most negative slope at the point defined in (2), and advancing STEPLN units along the bearing thus defined.

5) continuation, by fitting new (weighted) local surfaces as and when the positions of the advancing ends of the profile require it, and adding lengths alternately to the profile's upslope and downslope ends by a process analogous to steps (3) and (4). At each step, the terminating conditions to be described below are tested, and if one of them is violated, profile advance at that (upslope or downslope) end is terminated.

When termination has been achieved at both ends of the profile, the program moves on to the next point of origin, for which the steps (1) to (5) will be repeated. Figure 4.3 shows the flow of logic in SLOPROFIL.2.

Appropriate values of some of the terminating variables will depend on the particular terrain in the area covered by the matrix : they are therefore required as input by the user to SLOPROFIL.2. In chapters 6,7 and 9 in particular the optimization of terminating variable values is described for the catchments studied in this research, using an objective matching process that involves comparison of SLOPROFIL.2-generated profile statistics with those from program G. The definition of the terminating variables themselves should have meaning in all topographies however, and is explained below.

Condition 1 : termination if a STEPLN advancing upslope/downslope deviates in bearing by more than a threshold value (held in variable ORCJ, input by the user) from the last upslope/downslope step taken.

Condition 2 : termination if a STEPLN deviates in direction by more than a threshold value (held in variable GLOBAL, input by the user) from the overall profile direction, defined as the bearing of a line joining upslope and downslope ends of the profile as they have been traced so far. (Note : the program encounters condition 2 before condition 1, and therefore if the former has brought about termination, the profile receives a flag of '2' signifying termination by GLOBAL in the print-out at the end of the program, whether or not it would have terminated at the same point due to condition 1).

Condition 3 : termination at edge of study area.

Condition 4 : termination at upslope/downslope end when NHOPS number of points have been traced upslope/downslope from (and including) the

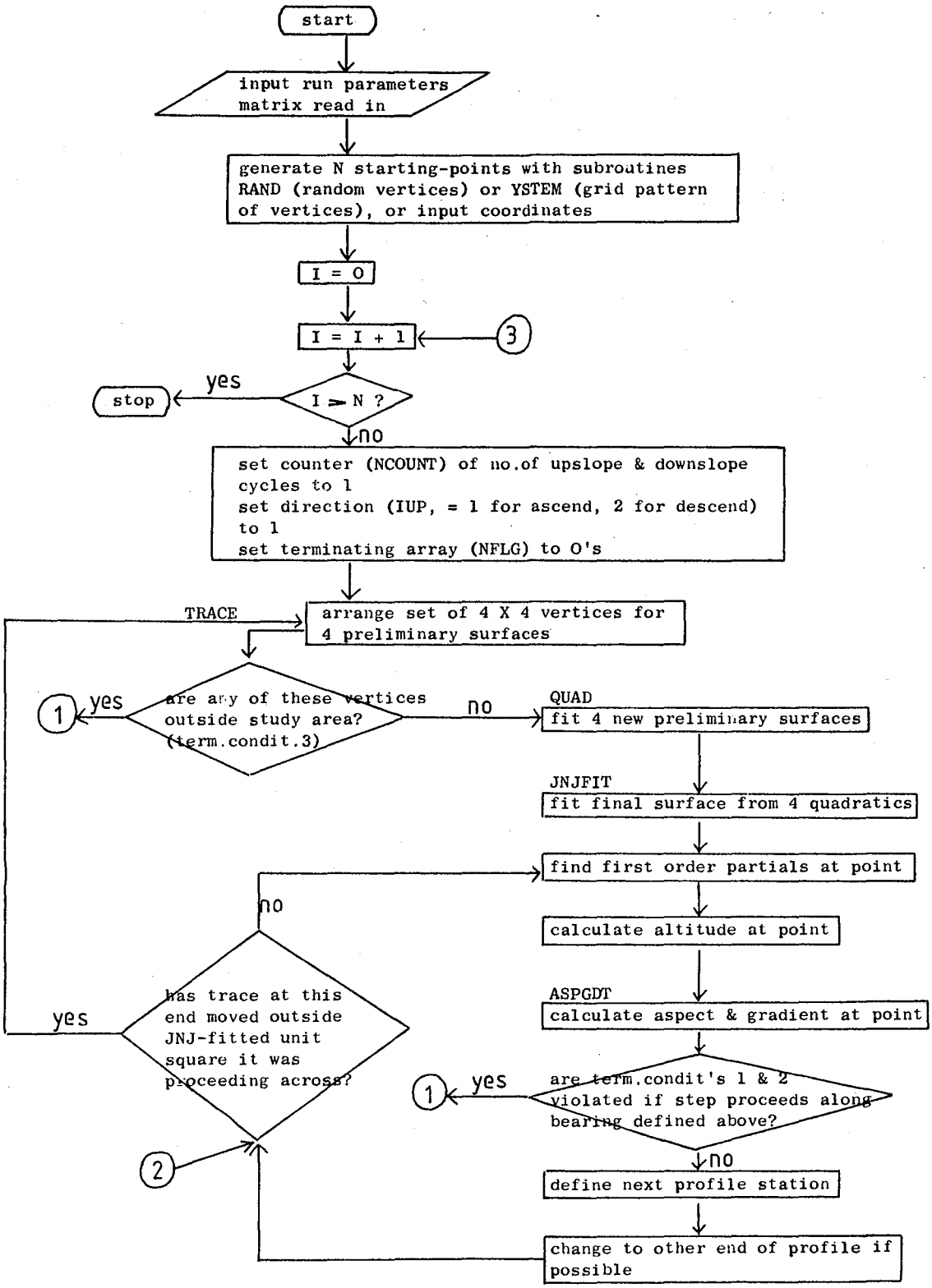


Figure 4.3 : SLOPROFIL.2 flowchart (Numbers in circles refer to locations in continuation of flowchart overleaf).

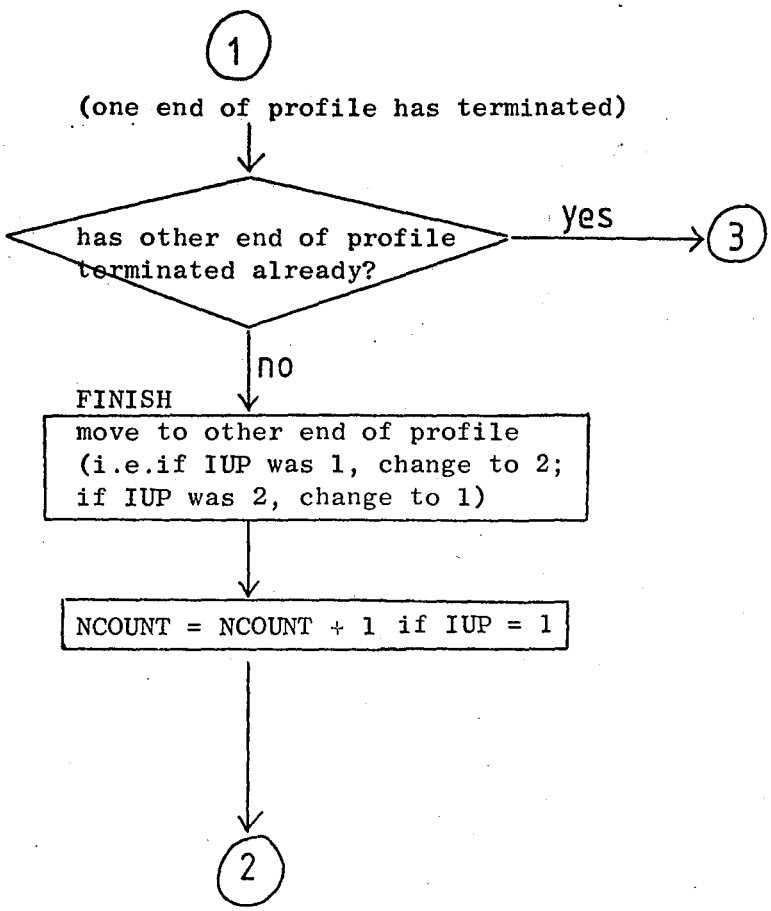


Figure 4.3 : SLOPROFIL.2 flowchart (continued) (Names in capitals are subroutine names if outside a box, variable names if inside one, with a couple of exceptions which are clear in their context. Convention for layout follows McCracken, 1972).

point of origin. NHOPS is input by the user, and represents a safety valve to terminate the profile before large amounts of time have been used up on computer, if the other geomorphologically-based terminating conditions (especially 1 and 2) do not. The value of NHOPS cannot be larger than the dimensions of the arrays to hold the details of the profile trace, at present set to 9999. This is a very long way outside the length of profile ever found necessary in this research, where 5 m steplengths were used for much of the time.

Condition 5 : termination in a flat area (i.e. first vertical derivative is zero). It is impossible to determine the horizontal derivative in this situation; profiling would also be terminated in the field on encountering such an eventuality, since if SLOPROFIL.2 is registering no slope this implies that at least 3 x 3 neighbouring altitudes are of the same height.

Condition 6 : termination at an angular reverse.

When the profile has advanced STEPLN units horizontally in the direction defined by the horizontal derivative during an upslope trace from a profile station, for example, it sometimes happens that the new profile station so defined is found to be at a lower altitude than the preceding one. This is because a change of surface slope direction has occurred between the two stations. The profile would terminate after this second station anyway (due to conditions 1 or 2), since the new horizontal derivative would deviate in bearing by a large amount from previous ones. Condition 6 is a refinement which acts to terminate the profile before that second station, so that no reverse angles are included at the ends of the resulting profile. Again, this is what a fieldworker would do.

Most profiles should terminate according to conditions (1) and (2), which are designed to prevent a profile from continuing down the

river course after reaching the base of a hillslope, or from continuing along a plunging divide up to the highest peak in the area at the upslope end of a profile. Lengths of profiles generated by SLOPROFIL.2 are very sensitive to the values of ORCJ and GLOBAL input, which is the subject of investigation in chapters 6, 7 and 9.

In summary, the user is allowed much free choice by SLOPROFIL.2 in the positioning of profile points of origin (random, grid pattern, or any set of points input by the user expressed in a compatible coordinate system). There is also freedom in the choice of values for ORCJ and GLOBAL : if, for example, it was desirable for profiles to continue down a hillslope and along the valley floor to the basin outlet (for some hydrological investigation for example), ORCJ and GLOBAL could both be set to 360°, in which case it would be very unlikely that they would bring about termination, however large the changes of bearing that the profile had to negotiate. The length of horizontal step taken in tracing profiles (analogous to ground surface length used in fieldwork) is also input by the user, and its variation between successive runs of the program can give the geomorphologist valuable insight into the effects of scale of measurement on results for his catchment. This issue is explored for the Gara and Netherhearth in chapter 8.

This section has dealt with the way in which SLOPROFIL.2 constructs profiles <u>given</u> the local surfaces that it is to trace them across. The following section gives details of the fitting of the local surfaces in subroutine JNJFIT of the program : this is important because the success with which such surfaces approximate the situation in real terrain will govern the success of SLOPROFIL.2 in producing realistic slope profiles.

4.4 Subroutine JNJFIT

Part 1

Each altitude matrix vertex (excluding the peripheral row and column on each side) is the centroid of a quadratic surface fitted to 3 x 3 vertices by subroutine QUAD, with a 'roving' coordinate system as portrayed in figure 4.4. (The coordinate system is 'roving' in the sense that each set of 3 x 3 vertices to be analysed in QUAD is given this coordinate system, no matter where the points lie in the matrix-wide coordinate system that starts in the north-west corner of the map).

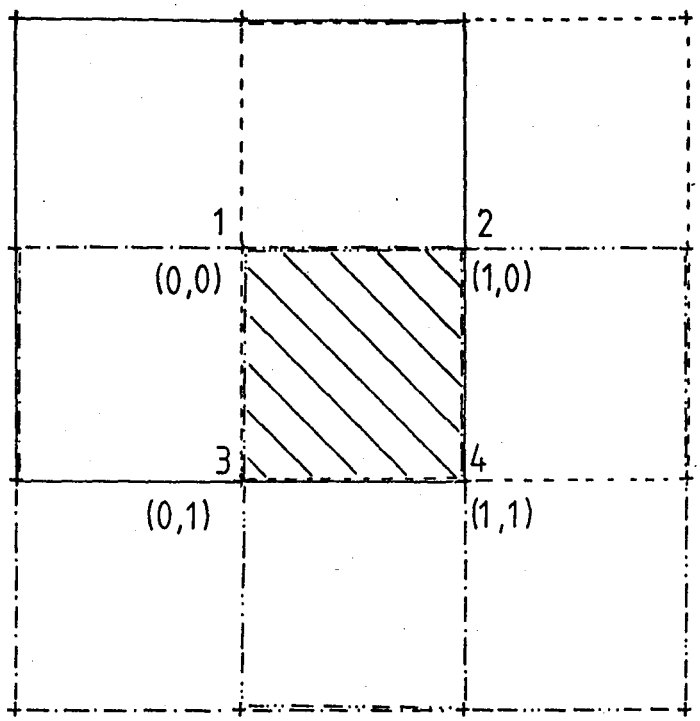
As these quadratic surfaces stand, (a) they overlap each other, and (b) there is no guarantee of a smooth progression from one to the next. Therefore a weighting function must be applied to combine overlapping quadratics and ensure continuity from one overlap zone to the next, as was mentioned above. If each quadratic as depicted in figure 4.4 is called a 'preliminary' fit, the weighting function will combine these to determine a 'final' fit to apply over a unit square (between 2 x 2 vertices) as depicted in figure 4.5. This figure shows that a new 'roving' coordinate system is operative here, with origin at the upper left-hand corner of the unit square of final fit. Points labelled 1,2,3 and 4 on figure 4.5 are the centroids of the four quadratics input to the weighting function (note that this numbering will be retained throughout subsequent discussion).

The coordinates of quadratics 2,3 and 4 must be transformed since their centroids need to become the points (1,0), (0,1) and (1,1) respectively in the new roving coordinate system applied to the final square (these points were all (0,0) in the roving coordinate systems of their respective preliminary fits, as in figure 4.4). Thus the quadratics expressed in the final coordinate system are

for 1) $z_1 = a_1x^2 + b_1y^2 - c_1xy + d_1x - e_1y + f_1$ equation 4.1
(i.e. as output by subroutine QUAD)

+	+	+
(-1,-1)	(0,-1)	(1,-1)
+	+	+
(-1,0)	(0,0)	(1,0)
+	+	+
(-1,1)	(0,1)	(1,1)

Figure 4.4 : Coordinate system for preliminary fits (quadratics)



K E Y

boundary of area of validity of
——— quadratic 1
- - - - - quadratic 2
—·—·— quadratic 3
—··—··— quadratic 4

area of final fit

+ vertex (labelled where appropriate with number of quadratic of which it is the centroid, and with coordinates, expressed in the coordinate system of the final fit)

Figure 4.5 : Diagram to show how each set of 4 quadratics (preliminary surfaces) are combined in one unit area of validity of a final (weighted average) surface.

for 2) $z_2 = a_2 (x-1)^2 + b_2 y^2 - c_2 (x-1)y + d_2 (x-1) - e_2 y + f_2$ 4.2

for 3) $z_3 = a_3 x^2 + b_3 (y-1)^2 - c_3 x(y-1) + d_3 x - e_3 (y-1) + f_3$ 4.3

for 4) $z_4 = a_4 (x-1)^2 + b_4 (y-1)^2 - c_4 (x-1)(y-1) + d_4 (x-1) - e_4 (y-1) + f_4$ 4.4

The weighting function chosen was devised by Jancaitis and Junkins (op.cit; also in Junkins, Miller and Jancaitis, 1973) to ensure agreement between adjacent final surfaces in value and first partial derivatives. It is a cubic function in x and y :

$$W = x^2 y^2 (9 - 6x - 6y + 4xy) \qquad 4.5$$

which is zero along the lines x = 0 and y = 0 and increases smoothly toward the point (1,1) - see figure 4.6. The factor $x^{n+1} y^{n+1}$ ensures automatic satisfaction of the constraint that the function and its first n partial derivatives be zero along the lines x = 0 and y = 0; since in SLOPROFIL.2 we are concerned with continuity in slope (first derivative), the weighting function in $x^2 y^2$ was adopted. Translation and rotation of this weighting function are required to apply it to quadratics 1,2 and 3 so that they can exhibit the smooth decline in W from 1.0 at their centroid to 0.0 at the two boundaries furthest from the centroid; that shown in figure 4.6 is for quadratic 4. This gives the weighting functions

for 1) $W_1 = (1-x)^2 (1-y)^2 (9 - 6[1-x] - 6[1-y] + 4[1-x][1-y])$ 4.6

for 2) $W_2 = x^2 (1-y)^2 (9-6x - 6[1-y] + 4x[1-y])$ 4.7

for 3) $W_3 = (1-x)^2 y^2 (9-6[1-x] - 6y + 4[1-x]y)$ 4.8

for 4) $W_4 = x^2 y^2 (9 - 6x - 6y + 4xy)$
(i.e. as quoted above, equation 4.5)

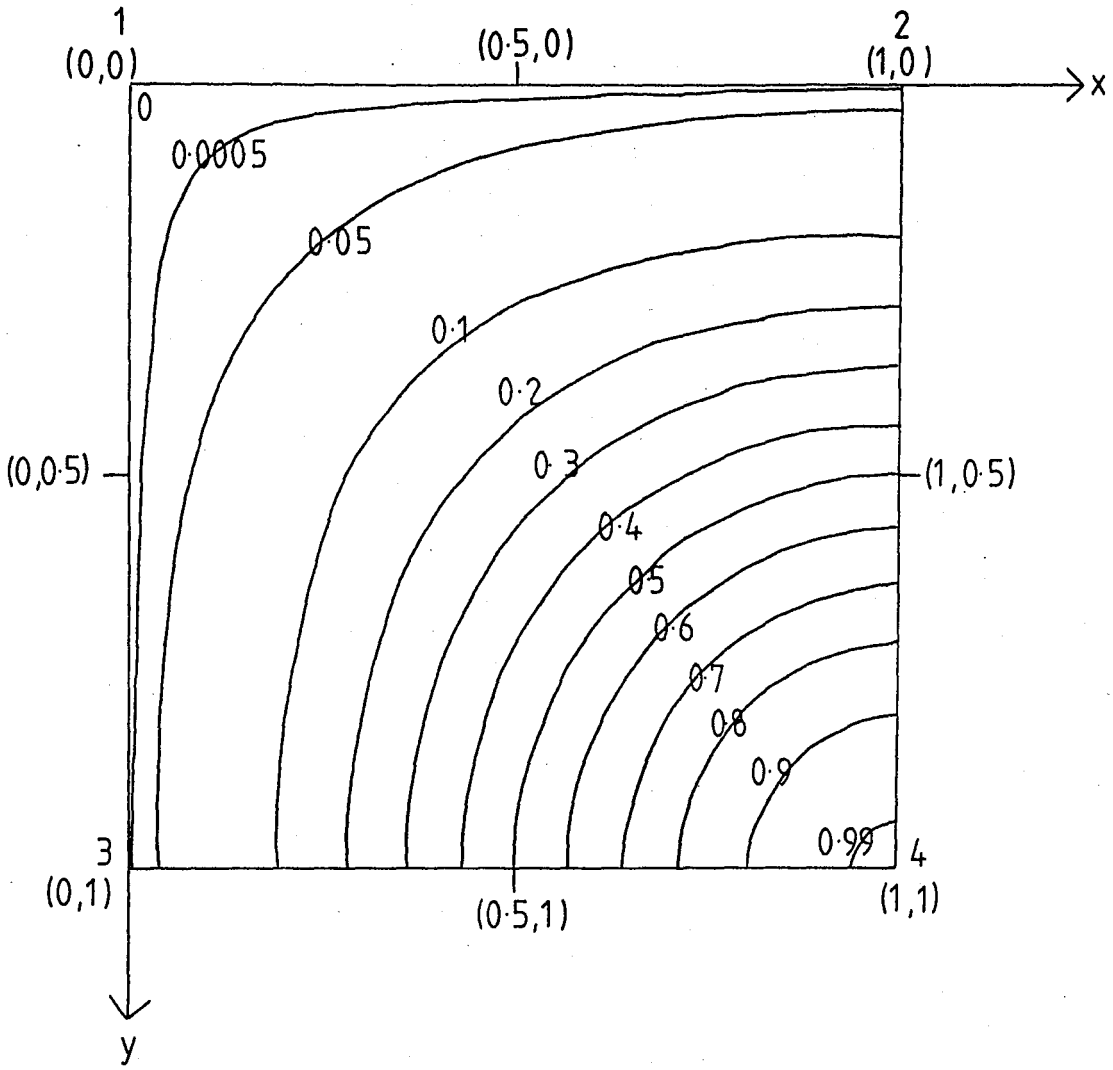


Figure 4.6 : Contours of the cubic weighting function, illustrated for quadratic 4 over a unit square of validity of a final fit.

Coordinates are expressed in coordinate system of final fit; points labelled 1, 2, 3 and 4 are centroids of quadratics with the same names (After Jancaitis & Junkins, 1973, 37)

and the final surface is the weighted average

$$z(x,y) = \sum_{i=1}^{4} W_i(x,y) \cdot z_i(x,y) \qquad 4.9$$

where

$z_i(x,y)$ are the preliminary (quadratic) surfaces (equations 4.1 - 4.4)

$W_i(x,y)$ are their appropriate weighting functions (equations 4.6-4.8 & 4.5)

The final surface is valid over the central square shared by the four quadratics : that is the square 1,2,3,4 in figure 4.5. Throughout this square

$$\sum_{i=1}^{4} W_i = 1.0$$

The way in which continuity in value and first partial derivatives is ensured between adjacent final surfaces can be illustrated by considering what happens to the weighting functions along boundary 3 - 4 in figure 4.5 for example. Looking first at value, it can be seen that here quadratics 1 and 2 can contribute nothing to the value of the weighted average surface, as their weighting functions are both zero along the line y = 1 (cf. figure 4.6); at point 3, quadratic 3 totally determines the value of the function ($W_3 = 1$); at point 4, quadratic 4 does ($W_4 = 1$); and various combinations of 3 and 4 (i.e. $W_3 + W_4 = 1$) apply along the line. Now consider the final square below the one we have been concerned with : that is, having its upper boundary along the line 3 - 4 in figure 4.5. For analogous reasons, its quadratics 1 and 2 totally determine the final surface along this boundary. Since these are the same quadratics as quadratics 3 and 4 of the original square, the same values are generated along the boundary whether viewed from the final square above it or below it.

Turning now to first partial derivatives, consider those <u>across</u> boundary 3-4 in figure 4.5 (i.e. controlled by the y-component of each

weighting function : the x-component controls variation only along the 3 - 4 boundary). W_1 and W_2 are zero along this line (see above), so they do not contribute at all here. Differentiating the weighting function for quadratic 3 (equation 4.8) with respect to y gives

$$dW_3/dy = 6y - 6y^2 - 18x^2y + 18x^2y^2 + 12x^3y - 12x^3y^2$$

therefore when y = 1 (along boundary 3 - 4),

$$dW_3/dy = 6 - 6 - 18x^2 + 18x^2 + 12x^3 - 12x^3$$

$$= 0$$

Differentiating the weighting function for quadratic 4 (equation 4.5) with respect to y gives

$$dW_4/dy = 18x^2y - 12x^3y - 18x^2y^2 + 12x^3y^2$$

therefore when y = 1 ,

$$dW_4/dy = 18x^2 - 12x^3 - 18x^2 + 12x^3$$

$$= 0$$

Analogous results apply for all four weighting functions across all four boundaries. The along boundary (x-) component of W_3 and W_4 is not zero, but it is the same whether calculated from W_3 and W_4 or from W_1 and W_2 of the final square below boundary 3 - 4 on figure 4.5, since the weighting functions for the quadratics centred at each corner of a final square are simply translations and rotations of each other. Thus since weighting function first derivatives are all zero across a final square boundary, and agree along these boundaries, no discontinuity in first derivatives between neighbouring final squares is imparted by the weighting function. Since the same quadratics are being used along the boundaries viewed from either side, there is naturally no source of discontinuity from them either.

The constants in equation 4.9 above are calculated in part 1 of JNFIT using the coefficients a to f of the four quadratics input. The sequence of operations in this subroutine is shown in figure 4.3.

Part 2

A profile is being traced in a series of STEPLN's across a JNJ-fitted square. It has reached the point $x = A = r\cos\theta$, $y = B = r\sin\theta$ (see figure 4.7). Substituting $r\cos\theta$ for every x in equation 4.9, and $r\sin\theta$ for every y, then differentiating with respect to r and allowing r to equal 0 causes all terms, except those that were in r before differentiating, to disappear. This greatly simplifies matters. Therefore to ensure $r = 0$ on differentiating, each profile station (point $x = r\cos\theta$, $y = r\sin\theta$) has in its turn to become the origin of the coordinate system for the final square - this is SLOPROFIL.2's third roving coordinate system. (First roving system : each preliminary surface is (0,0) at its centroid in subroutine QUAD; second roving system : each final square is (0,0) at its upper left-hand corner in part 1 of JNFIT. Since the latter is the more normal situation for the final square - the change in the final square's coordinate system being discussed here is entirely localized in part 2 of JNJFIT - it is this coordinate system that is being referred to in places in the text or figures where the 'coordinate system of the final fit' is mentioned - unless it is specified that the subject is the coordinate system used in part 2 of JNFIT).

If this new coordinate system is referred to by x',y'; then to differentiate at $x = r\cos\theta$, $y = r\sin\theta$, that point must be thought of as $x' = x - r\cos\theta$, $y' = y - r\sin\theta$. Therefore each x must be replaced by $(x' + r\cos\theta)$, each y by $(y' + r\sin\theta)$, so that differentiation can take place with respect to x' and y'. This is the derivation of part 2 of JNJFIT.

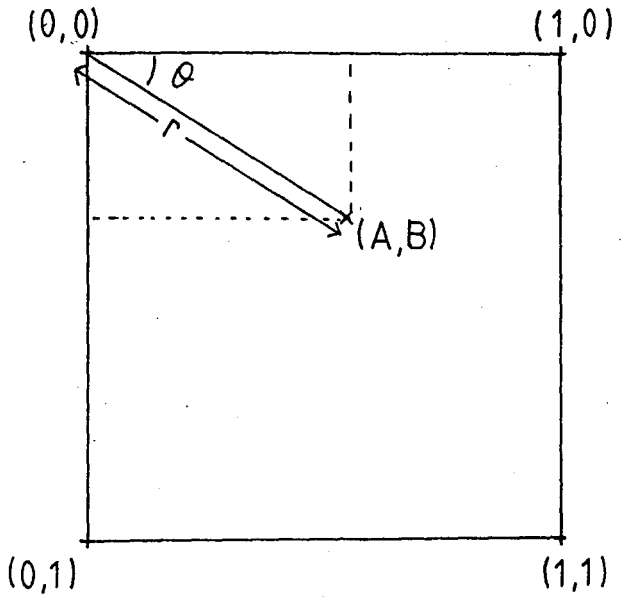


Figure 4.7 : Diagram to illustrate the application of part 2 of subroutine JNJFIT to a profile that has reached a point (A,B) in a final square.

Coordinates are expressed in coordinate system of final square (as applied in part 1 of JNJFIT).

Part 3

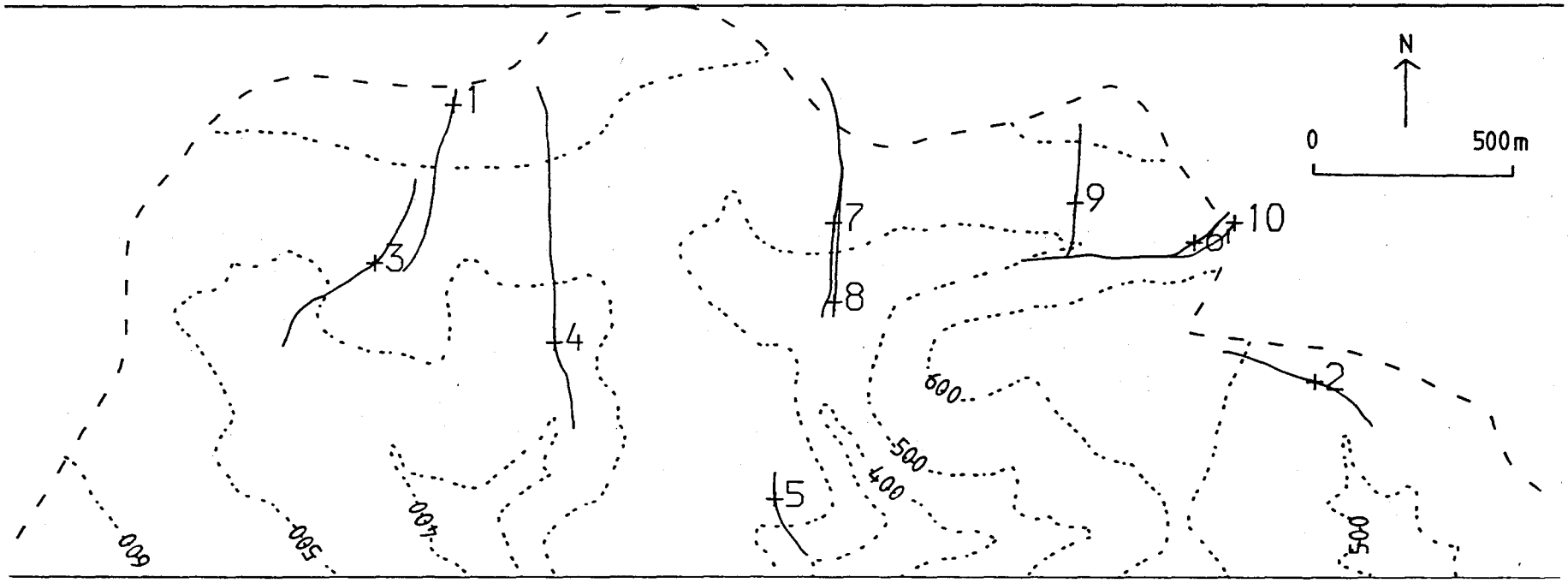
This simply involves substituting the current values of x and y into the equation whose coefficients were calculated in part 1, to derive the altitude at that point.

4.5 Preliminary validation of program SLOPROFIL.2

Figure 4.8 shows the very considerable improvement when a profile is allowed to pass between matrix vertices as in SLOPROFIL.2, rather than being constrained to pass from vertex to vertex as was the case with SLOPROFIL.1 (compare with figure 4.2). Much more will be said in the next chapter on how SLOPROFIL.2 profiles compare with those measured in the field.

In view of Cox's (1981) criticisms of Ongley's (1970) and Young's (1971) profile-analysing programs, that results are dependent on direction of data processing, it was felt important here to compare profiles traced up and down the same slopes. Since a profile advances in SLOPROFIL.2 by proceeding in the direction defined by the horizontal derivative at the current profile station (section 4.3), there is likely to be some difference in the path defined over a STEPLN of hillslope by a profile proceeding downslope according to a derivative obtained at the point above the STEPLN, and a profile proceeding upslope according to a derivative obtained at the point below the STEPLN. Only if the derivatives at these two points were identical, would the trace between them be the same whether traced up- or downslope. Derivatives at two points would become increasingly similar as the distance between them (STEPLN) shrank to zero.

The truth of these statements is borne out by the results of two experiments carried out on computer for the slopes whose bearings over



K E Y
See figure 4.2

Figure 4.8 : Slope profiles generated by SLOPROFIL.2 from the same 10 randomly-located vertices as used in figure 4.2, in the northern part of the Gara matrix at 50 m mesh.

successive 5 m lengths are shown in figure 4.9. Computer profiles were commenced at the base of these two slopes and traced up them using 5 m steplengths; the coordinates of the profile stations at the crests of the slopes were noted and input to SLOPROFIL.2 which then traced downslope from those points using the same steplengths. By the time it reached the base of the 335 m long slope (figure 4.9(A)), the profile being traced downward was 82.62 m from the base of the profile that had been traced upslope. On repeating the procedure with 1 m steplengths over the same slope however, the profiles were found to have diverged through 26.12 m : a considerable improvement. These results are an argument for starting profiles around the mid-point of a slope rather than at its extremities, where divergences could be expected to be greatest by the end of the slope. The direction-dependence must also feature in fieldwork however, where the surveyor takes a visual derivative at a point or locality, and advances along the bearing dictated by it for some length - in fact in the case of many slope profile studies, one bearing is retained throughout the slope's length (as discussed in chapter 2). Such a procedure would not have been justifiable for the profile whose bearings are displayed in figure 4.9(A), which is curved in plan and therefore provided a severe test for profile divergence with SLOPROFIL.2. Bearings along the slope displayed in figure 4.9(B) show some scatter also, but they are more clustered about a single mode than is the case for figure 4.9(A)'s distribution, which is bimodal. Computer profiles traced up and down the 455 m long 4.9(B) slope using 5 m steplengths diverged through only 7.43 m , and with 1m steplengths this narrowed to a negligible 2.12 m .

It is not very meaningful to state an average amount of time that SLOPROFIL.2 takes to trace a profile, because this will depend on the matrix mesh size (more detailed mesh will necessitate more fitting of

245 ·	8
246 ·	123
247 ·	026
248 ·	36778
249 ·	0035699
250 ·	024677
251 ·	37
252 ·	38
253 ·	0133477
254 ·	33678
255 ·	014567899
256 ·	5
257 ·	237
258 ·	156
259 ·	000
260 ·	9
261 ·	
262 ·	8
263 ·	
264 ·	7
265 ·	
266 ·	5
267 ·	
268 ·	1
269 ·	5
270 ·	9

A

122 ·	99
123 ·	67
124 ·	
125 ·	01
126 ·	99
127 ·	
128 ·	7
129 ·	28899
130 ·	1478
131 ·	466
132 ·	567
133 ·	57799
134 ·	123566
135 ·	01223344456668
136 ·	002455
137 ·	011344569
138 ·	0247899
139 ·	0011
140 ·	0223555
141 ·	1355
142 ·	6
143 ·	9
144 ·	
145 ·	
146 ·	
147 ·	1
148 ·	
149 ·	
150 ·	1
151 ·	
152 ·	7

B

Figure 4.9 : Stem-and-leaf plots* showing aspect (in degrees) of each 5 m length in two profiles traced upslope in the Gara catchment by SLOPROFIL.2.

* Constructed as explained in figure 2.17.

surfaces, and so take longer - other things being equal), the size of steplength used, and the length of slope to be traversed. To give an idea of roughly the amount of time involved : SLOPROFIL.2 takes approximately 0.2 CPU seconds to trace a 500 m profile using 5 m step-lengths on a matrix at 100 m mesh - that is, to fit about 5 final surfaces and define 100 steps along a contour-orthogonal path. This may be compared with the amount of time it took for the same (IBM 370/168) computer to produce the Netherhearth matrix using GPCP, quoted in the previous chapter.

The terminating condition GLOBAL (see section 4.3 - condition 2) is designed to give profiles whose extent is as independent as possible of the position of their point of origin in the landscape : thus to determine termination by this condition, the bearing of each STEPLN is compared with that of the whole profile as it has been traced so far, rather than with the bearing of the initial STEPLN's either side of the point of origin for example. GLOBAL was also thought to mimic the action of a field surveyor, who would tend to terminate a profile when true slope started to follow bearings very different from those defining the profile as measured so far (see chapter 2).

The condition attached to ORCJ (see section 4.3 - terminating condition 1) has a more local application, in preventing a profile from undergoing a sudden change in bearing. In smooth topography such as the 50m Gara matrix modelled with local quadratics, ORCJ can be set to a low value (e.g. 10°), because sudden orientation changes are not necessary on a slope when using 5 m steplengths (for example) which are free to follow the direction indicated by the horizontal derivative at successive profile stations. This is in contrast to the situation in the field, where a change of bearing with each ground surface length would be time-consuming and prone to disturbance by very small-scale

features, so that in the Gara survey a constant bearing was followed for successive 30m lengths (chapter 2), sometimes necessitating abrupt changes in orientation between these lengths (table 2.1).

Table 4.1 shows the reasons for termination of the profiles depicted in figure 4.8. It can be seen that although ORCJ is set to a low value of 10°, it relatively rarely causes termination in the Gara, while a value of GLOBAL of 35° more frequently does so. Much more will be said on the appropriate values of terminating variables ORCJ and GLOBAL in chapters 6, 7 and 9.

Table 4.2 shows a quantitative description of the top part of profile 1 on figure 4.8, output by SLOPROFIL.2. The sixth column (bearings of STEPLN's) shows that this profile, which looks relatively straight in the figure, frequently undergoes orientation changes of about 1.5° between successive STEPLN's. Columns 4 and 5 of that table show, respectively, the gradient obtained as a first derivative at a profile station, and the actual gradient of the STEPLN calculated from the difference in altitude of its two bounding profile stations. It is encouraging to see that the differences between these two columns of figures are not great; if they were, it would indicate that 5m steplengths were an over-generalization of the topographic variability obtainable as a point-based derivative, and would imply that program G(which uses the latter approach) and profiling (which uses the steplength approach) did not produce consistent results.

Output such as table 4.2 from SLOPROFIL.2 is interesting but consumes a lot of paper, or computer storage; therefore it is an optional feature of the program. More important is the output of gradients (derived from column 5 rather than column 4, to be compatible with field profiles), orientations and ground surface lengths to a subsidiary program which calculates summary statistics from the data, for comparison with output from program G. The program SLOPROFIL.2 is

Table 4.1 : List of terminating conditions and profile lengths for profiles depicted in figure 4.8, output by SLOPROFIL.2 (Steplengths = 5m)

PROFILE TERMINATES IF:-
1)TRACE SUDDENLY SWINGS THROUGH MORE THAN 10.0 DEGREES,OR
2)DEVIATES BY MORE THAN 35.0 DEGREES FROM OVERALL PROFILE DIRECTION,OR
3)EDGE OF STUDY AREA REACHED,OR
4)WHEN 9999 POINTS HAVE BEEN TRACED UP OR DOWN FROM START,OR
5)FLAT REACHED,OR
6)REVERSE IN SIGN OF SLOPE ANGLE

PROFILE NO.	UPSL.END	DOWNSL.END	HORIZ.LENGTH (m)
1	1	2	485.0
2	2	2	425.0
3	2	1	565.0
4	3	2	875.0
5	2	2	240.0
6	2	1	560.0
7	2	2	605.0
8	2	2	610.0
9	3	2	335.0
10	3	1	565.0

Table 4.2 : Description of crestal portion of profile 1 on figure 4.8, output by SLOPROFIL.2

```
GRID MESH IN M IS  50.00
MULTIPLY BY 0.3048 TO CONVERT HEIGHTS TO METRES
LENGTH BETWEEN PROFILE STATIONS CONSTANT AT   5.000 METRES
PROFILE TERMINATES IF:-
1)TRACE SUDDENLY SWINGS THROUGH MORE THAN  10.0 DEGREES,OR
2)DEVIATES BY MORE THAN  35.0 DEGREES FROM OVERALL PROFILE DIRECTION,OR
3)EDGE OF STUDY AREA REACHED,OR
4)WHEN 9999 POINTS HAVE BEEN TRACED UP OR DOWN FROM START,OR
5)FLAT REACHED,OR
6)REVERSE IN SIGN OF SLOPE ANGLE

STARTING FROM   10 RANDOMLY-PICKED VERTICES
```

CO-ORD S		CALC. ALT.(M)	1ST VERT. DERIV.	GRADT.	ORIENT.	REASON FOR TERMINATION	
59.16	5.22	194.09	0.175			1	
				0.402	194.326		
59.13	5.31	194.06	0.640				
				0.851	190.037		
59.12	5.41	193.98	1.045				
				1.197	188.918		
59.10	5.51	193.88	1.328				
				1.413	189.071		
59.08	5.61	193.75	1.477				
				1.501	190.027		
59.07	5.71	193.62	1.509				
				1.491	191.568		
59.05	5.81	193.49	1.466				
				1.439	193.267		
59.02	5.90	193.37	1.416				
				1.418	194.036		
59.00	6.00	193.24	1.440			START-PT	1(ALT. 193.24 M)
				1.514	194.036		
58.98	6.10	193.11	1.596				
				1.686	192.928		
58.95	6.19	192.96	1.780				
				1.875	192.032		
58.93	6.29	192.80	1.968				
				2.056	191.530		
58.91	6.39	192.62	2.140				
				2.215	191.445		
58.89	6.49	192.43	2.284				
				2.341	191.746		
58.87	6.59	192.22	2.393				
				2.434	192.394		
58.85	6.68	192.01	2.470				
				2.498	193.343		
58.83	6.78	191.79	2.523				
				2.546	194.531		
58.80	6.88	191.57	2.569				
				2.596	195.848		
58.78	6.97	191.34	2.627				
				2.667	197.120		
58.75	7.07	191.11	2.700				
				2.719	198.300		
58.71	7.16	190.87	2.736				
				2.755	199.932		
58.68	7.26	190.63	2.779				
				2.816	201.834		
58.64	7.35	190.39	2.862				
				2.925	203.686		
58.60	7.44	190.13	2.997				
				3.085	205.163		

reproduced for reference in appendix 1a; the subsidiary program used algorithms to calculate moment-based summary statistics taken from G; it is not worth reproducing in the thesis as it is not original. Output in the format of table 4.1, and maps like figure 4.8, are of vital importance and always generated by SLOPROFIL.2.

4.6 Concluding remarks

This chapter has described the construction of a program SLOPROFIL.2 to draw contour orthogonals from altitude matrix data, using several ideas gained from field profile survey but - crucially - never violating the condition of orthogonality to contours. It has been shown that allowing the profiles freedom to trace any path (without being constrained to pass through matrix vertices), using interpolation based on locally-valid quadratics ensured first-order continuity across boundaries by Jancaitis and Junkins' weighting function, produced results far superior to simply following vertices (compare figures 4.2 and 4.8).

Care has been taken to minimize the extent to which profile length is an artefact of the position on a slope of its point of origin. The terminating variables ORCJ and GLOBAL act on the profile as it 'grows' upslope and downslope by alternate steplengths from its point of origin : if the trace was to proceed first upslope all the way, and then downslope all the way, from the point of origin (as was the case in an earlier version of SLOPROFIL.2), the length of the downslope trace would depend greatly on the amount of orientation change achieved by the upslope trace, so that if the latter was a large amount, the downslope trace would only be able to achieve a small orientation change before termination due to GLOBAL, and the profile might never reach the base of the slope therefore. Absolute independence of profile

extent from the location of its point of origin could only be guaranteed by allowing the profile to proceed for a long way in both upslope and downslope directions, and later truncating it according to consistent criteria : this would be wasteful of computer resources hower; it is argued here that the procedure adopted in SLOPROFIL.2 is satisfactory.

SLOPROFIL.2 appears to produce realistic profiles (figure 4.8); it is now important to find out how such profiles compare with the same contour orthogonals measured in the field, in the next chapter.

4.7 Notation

a,b,c,d,e,f constants in the quadratic equations

θ angle between line joining a point to the origin of the final square it is in, and the line $y = 0$ of that final square

I counter of number of profiles in SLOPROFIL.2

i subscript which varies from 1 to 4 to denote the 4 surfaces being combined in a final square of fit by SLOPROFIL.2

N number of points of origin to be used by SLOPROFIL.2

n the desired number of partial derivatives to be continuous across a final square boundary. In SLOPROFIL.2 therefore, $n = 1$

r distance of a point from the origin of the final square it is in

W value of Jancaitis and Junkins' weighting function applied within a final fit in JNJFIT of SLOPROFIL.2

x,y two perpendicular coordinate directions in the horizontal plane, in the 'roving' coordinate system applied to final fits in <u>part 1</u> of subroutine JNJFIT in SLOPROFIL.2

x',y' two perpendicular coordinate directions in the horizontal plane, in the 'roving' coordinate system applied to final fits in <u>part 2</u> of subroutine JNJFIT of SLOPROFIL.2

z approximation to height of real terrain achieved by SLOPROFIL.2 using functions in x and y

CHAPTER 5 : COMPARISON OF MATRIX-DERIVED LAND FORM PROPERTIES AND GARA FIELD PROFILE DATA

5.1 Introduction

5.2 The issue of sampling land surface form using map and field data

5.3 Comparison between matrix-derived information from G and data from field profiles

i. Characteristics of frequency distributions

ii. Relationships

5.4 Computer profiles from matrices : comparisons with fieldwork

i. Accuracy of field data

ii. Fidelity in path followed (map position of profiles)

iii. Fidelity in shape (vertical section) of profiles

iv. Similarity in gradient

5.5 Concluding remarks

5.6 Notation

5.1 Introduction

This research has so far outlined the generation of land form data by three routes : slope profile survey in the field (chapter 2), manipulation of map-derived altitude matrix data by Evans' program G (chapter 3), and construction of slope profiles from altitude matrices with program SLOPROFIL.2 (chapter 4). All of these methods yield measurements of altitude, gradient, aspect, and profile curvature; and from some of them plan curvature information is available as well.

In section 5.3 of this chapter, selected summary statistics for the attributes of land form listed above, obtained from the Gara matrix by manipulation with program G, will be compared with data from field-surveyed profiles to evaluate the ground truth of matrix data from maps. The output from G will be referred to as matrix-G information, to distinguish it from data from SLOPROFIL.2, also derived from matrices.

In section 5.4, field profiles are compared qualitatively and quantitatively with profiles generated by SLOPROFIL.2 from the same points of origin in the Gara catchment. This comparison tests the relevance to fieldwork of results from that program, which is necessary before profiles generated on computer can be used to make recommendations on field profile sample size and design in subsequent chapters.

Before all this however, it is necessary to explain in more detail the grounds on which statistics from profiles and from matrices are to be compared, so that terms like 'representative sampling' are not permitted to appear undefined, but can be understood in the context of the aims of the study.

5.2 The issue of sampling land surface form using map and field data

As was stated in chapter 1, a broad aim of this research is to use altitude matrix data to plan efficient field profiling studies. It is assumed that land form attributes from an altitude matrix (as obtained by program G, described in section 3.7) are an unbiassed sample of those attributes over the entire matrix area, because it is not envisaged that land forms at the (drainage basin) scale of interest of this study have regular periodicities which coincide with a systematic sample of altitudes (see discussion in section 1.3). Profiles, however, have a more insecure sampling basis, as there is little knowledge of how to generate a set of lines that is an unbiassed sample of a land surface, as was explained in chapters 1 and 2. Therefore this thesis will concentrate on analysis of those attributes of land form obtainable from profiles that can also be calculated using G from matrices : altitude, gradient, aspect, and profile and plan convexity. The aim is to generate a profile sample that is an unbiassed estimator of the matrix-wide distributions of these attributes.

It is recognized that there are other criteria for selecting slope profiles : some profilers are not interested in the issue of area-wide sampling at all. However this issue has been neglected in the literature, as earlier chapters have shown, and those who have paid the matter some attention, such as Parsons (quoted in section 1.2), have concluded pessimistically that very large samples of profiles are needed to estimate land form attributes over a drainage basin. It is possible that a completely new approach will be able to find a way through this deadlock : as Williams says 'In general, to cut the variance in half, you must double the sample size. This is one of the reasons why the biggest gains in efficiency are often made by clever sampling designs and estimators, rather than by increased sample size' (1978, 214).

An important requirement of many process studies is a knowledge of the spatial representativeness of results; if a way of gauging the spatial representativeness of localized topographic samples (slope profiles) can be devised here, the geomorphologist linking process to form can begin to get some of this knowledge. First it is important to be clear about what is meant here by spatial representativeness. 'Samples fall short of being miniatures [of the parent population] ... because of (1) selection, (2) sampling fluctuations,and (3) the effective impossibility of resemblance on many traits at once' (Kruskal and Mosteller, 1979c, 250). In this research, the land form attributes from the sample are compared with those from the population (matrix) for agreement chiefly in moment-based summary statistics : mean, standard deviation, skewness, and kurtosis. Agreement in all these parameters for the five land form attributes mentioned above would only be attained if the sample of attributes was an exact miniature of a parent population, which is unlikely,as the quotation states. Geomorphological knowledge has therefore to be brought to bear in the judgement of which statistics should have priority for agreement. For example it has already been shown (chapters 2 and 3) that standard deviations of profile and plan curvature are particularly sensitive to the scale of measurement, which gives an idea as to the difficulty of matching up these parameters between field samples and matrix populations. This research is more about quantifying the degrees of matching possible, than it is about hard-and-fast rules for profiling, because to a large extent the sample that a geomorphologist chooses will depend on the purposes of the study : guidelines are more useful than inflexible rules.

Not only will profiles generated from matrices be compared with matrix-wide attributes from G, but also - in the present chapter -

attributes from map-derived matrices will be compared with attributes measured in the field. It is an axiom in geomorphology that map- and fieldwork will produce different results, illustrated by a quotation from Strahler : 'while a fairly close agreement exists between field slope data and those taken from the best available topographic maps, the inconsistencies are of too great an order to permit significance studies between small groups of field and map data. It is advisable to use only the one type of data, preferably the field observations where these can be had' (1950a, 693). This researcher agrees with the first part of this quotation, but disagrees with the second. The use of significance testing in geomorphology must be approached with great caution in any case, since the rejection or non-rejection of the null hypothesis is based on the properties of a statistical distribution not necessarily relevant to geomorphic attributes that have persistence in space (autocorrelation). With regard to the second part of the quotation : many practical studies cannot afford the luxury of collecting all their data in the field, and this research is about how to obtain assistance from maps.

It is true that map-based data will not reproduce all the irregularities found in the field. Mark and Peucker (1975) have usefully distinguished three types of source of possible difference between field- and map-derived slope data; they are

1) differences between the true form of the land surface and the surface as shown on a topographic map (due to cartographic generalization);

2) differences introduced because the measurement increments used (analogous to STEPLN in SLOPROFIL.2,discussed in the previous chapter) are large with respect to the slope element one wishes to detect (due to cartometric generalization); and

3) differences due to an invalid method of estimation of slope.

The possibility of (3) has been discounted for program G by Evans (e.g. 1979, 31), and for program SLOPROFIL.2 by the preliminary validation in the previous chapter. The first two types of difference will be the subject of appraisal in the remainder of this chapter.

There is also a fourth source of difference : that due to errors in locating and measuring profiles in the field : the problems outlined in chapter 2 should be borne in mind during subsequent analysis of Gara field profile data. Ideally a field sample would have been taken which could be relied upon to provide unbiased estimates of terrain attributes of interest, and thus illustrate the characteristics of frequency distributions of land form data expectable on the ground. However this thesis is also about how to generate such a reliable field sample by profiling. Therefore in this chapter only an indication of the acceptability of the matrix data and some of the field variability not captured by them is possible.

5.3 Comparison between matrix-derived information from G and data from field profiles

5.3.i Characteristics of frequency distributions

The issue to be explored in this section is the comparability of terrain measurements taken from the matrix at a relatively coarse mesh with field measurements made with 5 m ground surface lengths (gsl's) as recommended in the BGRG Technical Bulletin (Young, 1974). That comparison incorporates the contrast between map- and field-based measurements as well as a contrast in scale of measurement, so in an attempt to isolate the effects of scale, some comparisons are made with field measurements interpolated over 50 m (horizontal) lengths. Also, results from matrix information thinned to 100 m mesh are compared with 50 m matrix results.

Figure 5.1 and figure 5.2 (main histogram) show frequency distributions of gradient for matrix-G at 50 m mesh and field profile data from 5 m gsl's respectively. They confirm that the coarser scale map-derived data do filter out some of the variability to be found in the field, in that tails on the distribution of field-measured gradients are fatter, and the upper one (towards higher values) longer, than in the 50 m matrix-derived gradient distribution. However the central tendencies of the two distributions are more similar, the field data having a mode at 4° and the matrix at 5°; both are also positively skewed distributions.

Figure 5.2 (inset) suggests the result of using a 50 m horizontal interval (instead of 5 m ground surface length) in field measurement : although the number of these values obtainable from the field survey information is not very large, it can be seen that this change of scale pulls in the tails of the distribution so that they are even shorter than in the matrix-derived gradient distribution. This difference between matrix data from a map at 50 m mesh and data from field profile stations 50 m apart would seem to contradict the intuitive expectation that field measurements would tend to capture more variability than map-derived measurements; the reason for it however is that the gradient from the matrix is a derivative, the tangent (at a grid intersection, or vertex, of an altitude matrix) to a quadratic surface fitted to the 50 m mesh data as was described in chapter 3. The gradients in main and inset figure 5.2 are for the inclination of an imaginary line joining two points on the ground surface 5 m apart along a true slope line (main figure) or 50 m apart measured horizontally (inset figure). This distinction is illustrated diagrammatically in figure 5.3.

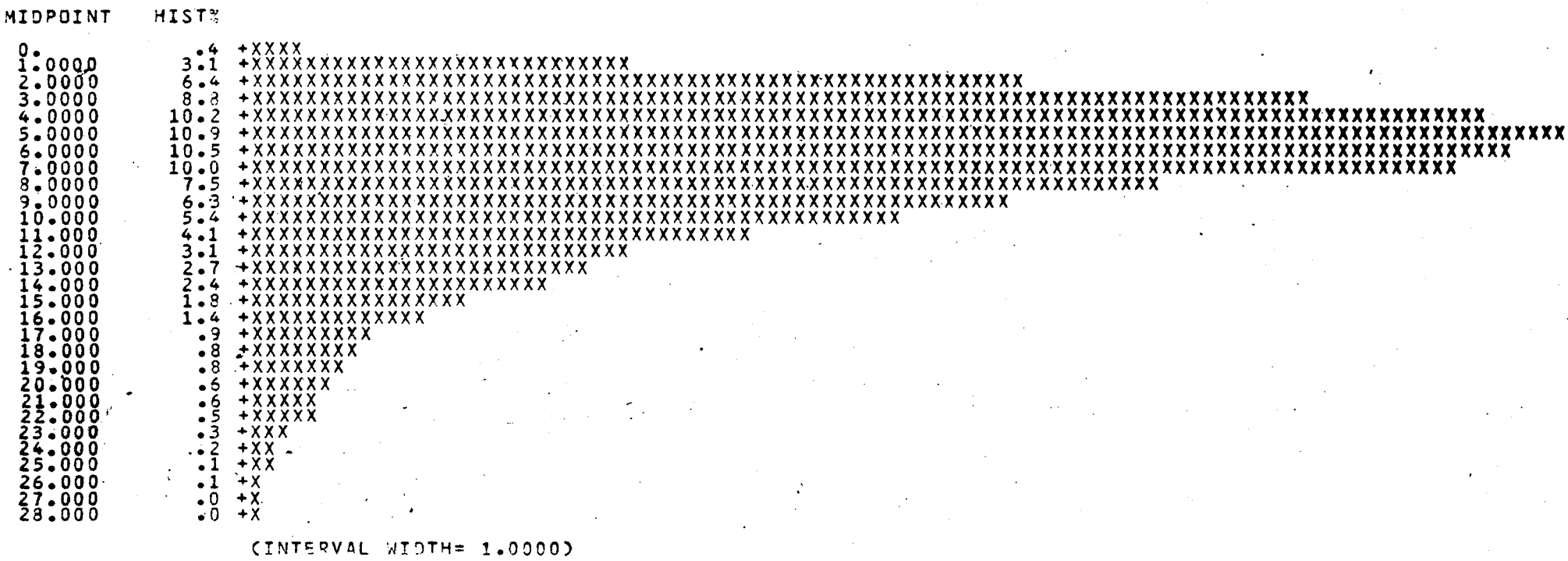


Figure 5.1 : Frequency distribution of gradient in degrees in Gara catchment, from altitude matrix at 50 m mesh analysed with 'G' (Each X = 13)

MIDPOINT	HIST%	COUNT
0.	1.1	19
1.0000	3.2	54
2.0000	6.4	107
3.0000	7.4	124
4.0000	13.0	219
5.0000	11.1	186
6.0000	8.6	144
7.0000	7.7	129
8.0000	6.3	106
9.0000	5.2	88
10.000	3.2	54
11.000	3.0	51
12.000	2.8	47
13.000	3.0	50
14.000	2.8	47
15.000	2.4	41
16.000	1.8	30
17.000	1.5	25
18.000	1.4	24
19.000	2.0	34
20.000	.7	11
21.000	1.5	26
22.000	1.7	29
23.000	.8	14
24.000	.5	9
25.000	.5	8
26.000	.1	1
27.000	0.	0
28.000	0.	0
29.000	.1	1
30.000	.1	1

MIDPOINT	HIST%	COUNT
0.	0.	0
1.0000	3.9	5
2.0000	6.5	10
3.0000	7.8	12
4.0000	13.6	21
5.0000	13.0	20
6.0000	5.8	9
7.0000	7.1	11
8.0000	8.4	13
9.0000	4.5	7
10.000	5.8	9
11.000	1.9	3
12.000	4.5	7
13.000	3.9	6
14.000	1.3	2
15.000	3.2	5
16.000	0.	0
17.000	1.9	3
18.000	1.3	2
19.000	1.9	3
20.000	.6	1
21.000	1.3	2
22.000	.6	1
23.000	.6	1

Figure 5.2 : Frequency distribution of gradient in degrees in Gara catchment, based on field profile survey data for 5 m ground surface lengths.
Main histogram : gradient as measured over each 5 m gsl (each X = 3)
Inset histogram : gradient over intervals of 50 m (measured horizontally), interpolated (linearly) between profile stations surveyed in the field (each X = 1).
Both histograms have the same class width as figure 5.1.

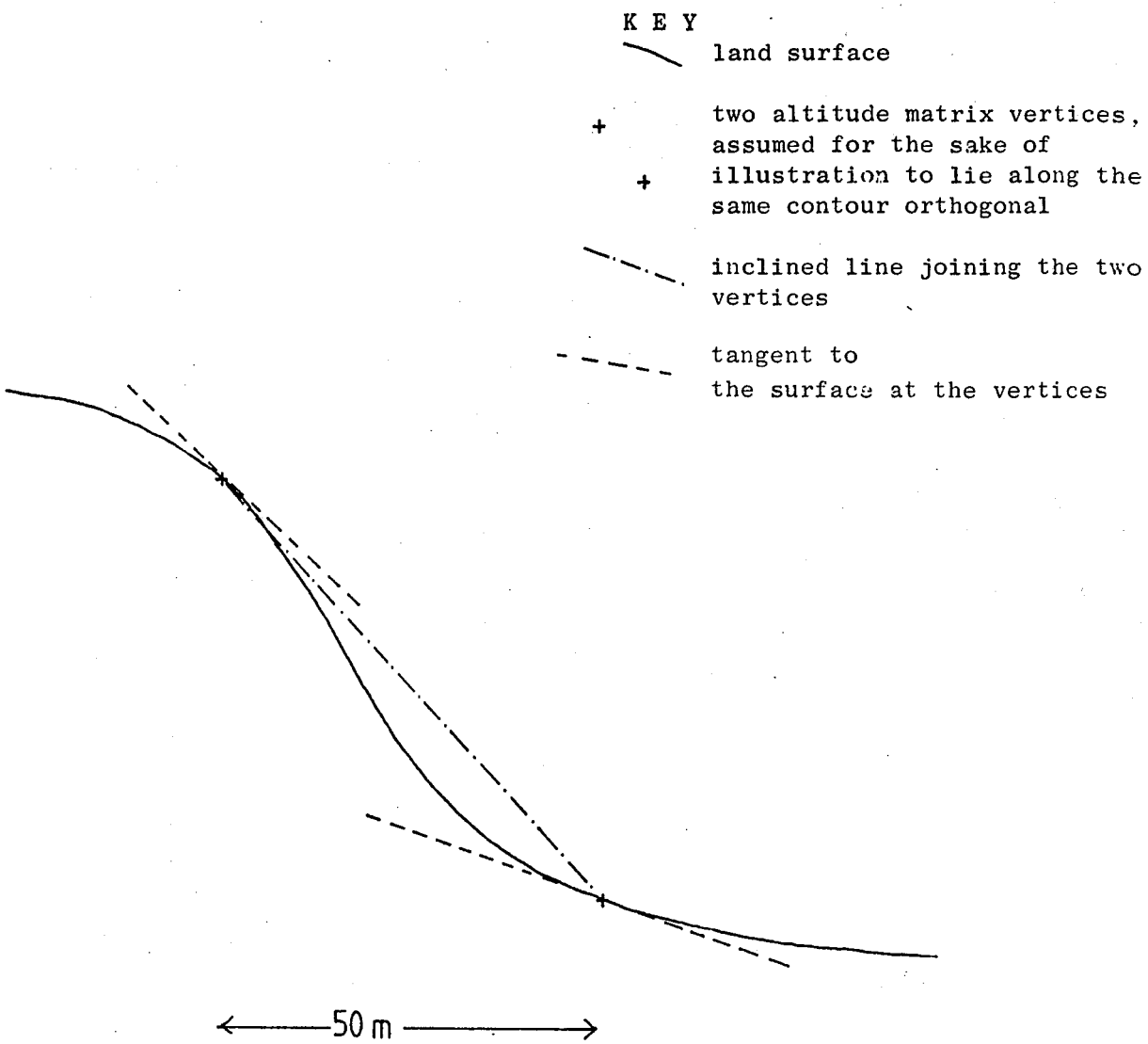


Figure 5.3 : Diagram showing a hypothetical vertical section through a hillslope, to illustrate the difference between inclined-line and point-based-derivative approaches to estimation of gradient.

Table 5.1 sets out summary statistics for the chosen land form attributes for the field survey (5 m gsl), field survey interpolated at 50 m horizontal lengths, field survey data using derivatives, and information from 50 m and 100 m mesh altitude matrices, in columns 1 to 6. The statistics confirm that 50 m matrix-G gradient has a lower mean and standard deviation than the 5 m gsl field gradient, and less extreme maximum and minimum, although not as curtailed as those of the 50 m interpolated field gradient. The 100 m matrix information is considerably more generalized still in its representation of mean and standard deviation of gradient. The high mean of the 5 m field gradient data may be due in part to undersampling of low-angled summit areas in the field, discussed in chapter 2, rather than being entirely due to the more detailed scale of measurement: it has already been stressed that the field data collected in the Gara cannot be treated as a reliable sample of the total landscape.

The gradient statistics in columns 3 and 4 were calculated from profile data by fitting successive two-dimensional quadratic functions to three neighbouring profile stations defined by 5 m gsl's measured in the field (column 3), and defined by 50 m constant horizontal lengths interpolated from the field measurements (column 4). This was done to harmonize the methods of calculating gradient for field and matrix data, and in order to comment on the assertion made earlier on in this sub-section that gradient from G escapes being as generalized as the mesh size would suggest because it is calculated as a derivative. Comparing columns 1 and 3, it can be seen that calculating gradient as the inclination of a 5 m gsl and as a derivative at profile stations placed 5 m apart up a slope makes little difference to the summary statistics obtained. This was also found when comparing derivative and inclined-line gradient statistics for computer-generated profiles (cf.table 4.2 columns 4 and 5) : for example for computer-generated profiles 1,2

Table 5.1 : Summary statistics from field survey according to the two sampling schemes employed in the Gara catchment, and from the matrix at 50 and 100 m mesh

		(1) Field grid & psbl, 5m gsl (fig's in brackets are profc. as det.by A.Young formula 2)	(2) Field grid & psbl, 50m horiz.constant lengths(fig's in brackets are profc. as det.by A.Young formula 2)	(3) Field grid & psbl, 5 m gsl,using derivatives	(4) Field grid & psbl, 50m horiz.constant lengths,using derivatives	(5) 50m matrix	(6) 100m matrix
ALTITUDE (m)	mean	127.17				120.59	118.78
	st.dev.	41.36				39.60	39.06
	skew	0.09				-0.40	-0.36
	kurt	-0.57				0.12	0.11
	max	213.88				214.99	209.87
	min	13.34				1.76	0.00
GRADIENT (°)	mean	8.05	7.03	8.12	7.51	7.40	6.40
	st.dev.	5.70	4.52	5.62	4.40	4.55	3.53
	skew	1.08	1.38	1.06	1.09	1.16	1.67
	kurt	0.48	1.66	0.34	0.93	1.43	1.67
	max	30.00	21.33	25.50	21.66	27.72	22.64
	min	-2.00	0.75	-1.25	1.05	0.17	0.08
PROFILE CURVATURE (°/100m) †	mean	2.12 (1.72)	2.33 (1.84)	1.72	1.84	-0.02	-0.02
	st.dev.	23.67 (37.58)	4.03 (5.46)	38.29	5.47	9.62	5.91
	skew	-0.32 (0.24)	0.55 (0.21)	0.25	0.21	-1.87	-1.53
	kurt	10.42 (21.54)	0.94 (2.07)	20.91	2.10	6.95	4.61
	max	175.00 (350.00)	14.90 (18.63)	353.23	18.73	33.83	18.54
	min	-140.00 (-350.00)	-8.29 (-18.09)	-350.38	-18.18	-74.97	-39.19
PLAN CURVATURE (°/100m) †	mean	-18.23				0.33	-7.48
	st.dev.	132.01				158.12	139.89
	skew	-0.72				-18.06	-21.27
	kurt	3.64				807.64	774.11
	max	332.50				2430.87	1145.91
	min	-420.00				-7657.09	-5307.40
No.of measurements		1622	95	1622	95	11525	2711

* Field planc statistics are quoted as measured over 20m either side of profile line and are calculated from a total of 24 measurements. † convention is convexity +ve , concavity −ve .

and 3 of figure 4.8 (having horizontal constant lengths = 5m), the mean and standard deviation of gradient as a first derivative were found to be 4.16 and 1.21° respectively; the same statistics for gradient as an inclined line were 4.16 and 1.20° respectively.

However, from comparison of columns 2 and 4 of table 5.1, it is apparent that when the measured length is increased to 50 m (measured horizontally), the inclined line gives a more subdued impression of gradient than the derivative (reflected in the differing means of the two sets), because the generalization involved in pretending that a slope is straight between two points 50 m apart is too great a departure from reality in this catchment (cf. the sort of situation illustrated in figure 5.3). Thus it is the case that statistics for gradient from G are more like those measurable in the field over 5 m gsl's than the resolution of the matrix (here 50 m) would suggest, because G uses derivatives : this is an important advantage.

The altitude statistics in table 5.1 imply that both grid and PSBL schemes in the field have over-sampled high-altitude areas, which appears paradoxical in view of assertions put forward in chapter 2 that the field sample tended to neglect summit areas. The most likely explanation is that both grid and profile sampling baseline (PSBL) schemes undersampled slopes towards the catchment's outlet. This was probably the result of shorter slopes there : thus profile 19, in the catchment's headwater area, contributed a large number of measurements (175), of median altitude 198.22 m; by contrast profile 5, nearer to the mouth of the catchment, involved measurement of only 28 angles with median altitude 57.36 m. Omissions due to accessibility problems may have contributed : profile 2 was left out because of absence of permission to survey. It should also be remembered that in its blanket coverage, the matrix samples talweg areas, whereas profiles by definition cover

only hillslopes, which could in itself account for a higher average altitude in the latter case. Standard deviations of field and matrix-derived altitudes are comparable, suggesting that this is not a difficult parameter to estimate.

Profile curvature data are complicated by the fact that they reflect the influence of scale and method of measurement : firstly, as with gradient, it is predictable that a coarser resolution will tend to generalize the figures; secondly, the length over which profile curvature is measured is multiplied up to be expressed in degrees per 100 m , and only in the case of hills perfectly radial in vertical section would the influence of this multiplying factor disappear (see discussion in section 2.11). Also, in the case of the matrix, the figure for profile curvature is calculated as a second derivative over 1 m at a vertex and subsequently multiplied by 100 in G; in the field case it was calculated using information from three adjacent gsl's according to the following formula :

$$C_n = -100 \times \frac{\beta_{n-1} - \beta_{n+1}}{0.5D_{n-1}+D_n+0.5D_{n+1}} \qquad \text{(...A.Young formula 1)}$$

where C_n is profile curvature attributable to measured length number n in degrees per 100 m

β_n is gradient of gsl n in degrees

D_n is length of gsl n, in metres (After Young, 1974, 45)

Profile curvature was also calculated for the field data as a second derivative (from the two-dimensional quadratics fitted locally to adjacent profile stations); results are presented in columns 3 and 4 of table 5.1. Comparison of columns 1 and 3 shows that taking derivatives increases the standard deviation of profile curvature for

5 m gsl measurements by more than 50%. The reason for this is illustrated by the fact that a series of gradients of 5.0, 4.5 and 5.0° measured in the field produced an estimate of profile curvature for the central gsl of 0°/100 m by Young's formula 1, but the second derivatives of the local quadratic, calculated at the two profile stations either side of the central (4.5°) gsl, were found to be -10°/100 m and +10°/100 m respectively. Thus Young's formula 1 (so called here for reasons which will become apparent below) in effect compares gradients at lag two, and for a series of oscillating values rather than a steadily increasing or decreasing progression of numbers, this is likely to produce a dampening effect (if the three values quoted above had formed a steady progression such as 4.0, 4.5 and 5.0°, Young's formula 1 would have given a profile curvature value of 10°/100 m for the central gsl).

Comparing columns 2 and 4 of table 5.1 for profile curvature, it can be seen that the effect of taking derivatives in the 50 m horizontal constant length case is to produce less of an increase (of about 33%) in standard deviation than for the 5 m gsl case. This must be because information from the longer lengths is more likely to be consistently increasing or decreasing : more of the oscillation due to irregular ground is smoothed out at this resolution. It is surprising that the matrix at 50 m produces a higher standard deviation of profile curvature (column 5) than the second derivative for the 50 m field data (column 4) : it is possible however that bias has been introduced in the calculation of the latter statistic, since only the longer field profiles could furnish a sufficient number of measurements at 50 m horizontal constant interval to allow a quadratic to be fitted, and the longer profiles tended to be straighter in profile, such as profile 19; the shorter 'nose' slopes would be likely to yield the most extreme values of profile convexity.

Young also presents an alternative formula for calculating profile curvature, this time attributable to a profile station :

$$S_{n+1} = \frac{\beta_n - \beta_{n+1}}{0.5(D_n + D_{n+1})} \times -100 \qquad \text{(... A. Young formula 2)}$$

where (After Young, 1974, 45)

S_n is profile curvature attributable to profile station number n in degrees per 100 m (NB : profile station number n will be the upslope bounding station of gsl number n).

Rest of notation as for Young formula 1.

The result of using this formula (presented in brackets, table 5.1 columns 1 and 2) is to produce statistics much more similar to those for the second derivatives (columns 3 and 4). For the smoother profile data derived from the matrix using SLOPROFIL.2 however, the contrast between standard deviation of profile curvature as calculated by Young's formulae 1 and 2 is less acute : for the 15 PSBL profiles generated by SLOPROFIL.2 with ORCJ=10°, GLOBAL=35° (variable names were explained in chapter 4) and horizontal constant lengths=5 m , standard deviation of profile convexity as calculated by Young formula 1 was 11.84°/100m : by formula 2, it was 12.43°/100 m . In further analysis of profile data from SLOPROFIL.2 in this thesis, Young's formula 1 is used, as it was considered to be more comparable with gradient measurements from profiles, also attributable to a measured length rather than to a profile station. The magnitude of the underestimation (by about 5%) of standard deviation of profile curvature as a second derivative by this method should therefore be borne in mind.

The fact that the 50 m matrix-derived standard deviation of profile curvature is a good deal smaller than the 5 m field's (by Young formulae 1 or 2) implies that the generalization due to the coarse

mesh had more influence than the counterbalancing effect of taking derivatives rather than measuring over gsl's for this attribute. Profile curvature according to the evidence presented here is more affected by scale of measurement than is gradient : this accords with findings in previous chapters.

The field plan curvature figures are not numerous enough to be very reliable (number of readings = 24, in contrast to other field-measured attribute distributions based on 1622 measurements - see final row and footnote, table 5.1). By contrast with the case for profile curvature, standard deviation of field plan curvature appears to be very comparable with that from the matrix at 50 and 100 m mesh, which could imply that radial symmetry is a less artificial assumption in the horizontal plane as Troeh (1964, 1965) suggests. The very large figures for the maximum and minimum of plan curvature from matrix-G are a feature of low-angled areas such as rounded summits, where a practically infinite value of plan curvature could be envisaged; this effect was noticed in fieldwork too, but since most of the field measurements were taken nearer the middle of a profile (as Parsons recommends : see section 2.11), the summary statistics from the field do not reproduce these extremes.

To summarize, 5 m field and 50 m matrix-derived frequency distributions of altitude and gradient are fairly comparable; so also are standard deviations of plan curvature as far as the limited data for this suggest. The estimate of standard deviation of profile curvature by matrix at 50 m mesh is however less than half that calculated from the field data at 5 m gsl. The effect of calculating gradient and profile curvature as first and second derivatives in G, is to allow the matrix-derived measures of gradient in particular to approach field values more nearly than the constrast in their resolutions would suggest.

5.3.ii Relationships

Table 5.2 shows that the most consistent correlation picked up by all scales of measurement in the Gara catchment examined here is the negative one between altitude and gradient, confirming the observation already made that the Gara is a catchment of steep valleysides, especially towards its outlet, and gentler summits and headwater areas. The strength of this relationship declines as the scale of measurement becomes broader, according to the evidence presented in table 5.2; this indicates that the high gradient values found at low altitudes are progressively generalized out at coarser resolutions.

Both sets of matrix data also indicate a positive relationship between altitude and profile curvature, yet the relationship between these two attributes calculated from field data is negligible. This finding suggests that when viewed at a reconnaissance scale (50 m or 100 m between sampled points), profile curvature is predominantly negative in valley bottoms and positive on summit areas, but at the level of detail detectable with field measurements at 5 m gsl, this relationship does not hold. The field data produced a coefficient of -0.280 for the correlation between altitude and the modulus of profile curvature, implying that in detail the valleys appear more curved (convex and concave) in profile than the flatter summit and headwater areas.

The relationship revealed between profile and plan convexity in the field is interesting, reinforcing a picture of hollows concave in both directions, and 'noses' convex in both. This is possibly a finding characteristic of the Gara's topography, and not the universal case : Carson and Kirkby (1972) found an inverse relationship between contour curvature and profile curvature for areas chiefly in southern England (p.411), and also cite the extreme case of the perfect pediment,

Table 5.2 : Correlations, Gara data

	alt/gradt	alt/profc	alt/planc	profc/gradt	planc/gradt	profc/planc
Field grid & psbl, 5m gsl. no.of values = 1622	-.625	.030	-.053*	.008	-.143*	.435*
50 m matrix, no.of values = 11525	-.493	.346	.140	.035	.002	.131
100 m matrix, no.of values = 2711	-.392	.424	.138	.094	.079	.098

* Based on 24 measurements

on which contours are all convex and profiles all concave.

Parsons in his study of the relationship between profile and plan curvature within field-measured profiles using lengths and methods recommended by Young (1974), also discovered them to be relatively strongly, and positively, related. He found no such relationship between mean profile and mean plan convexity for each slope. He concludes that 'if plan curvature does affect hillslope processes and is thereby related to profile curvature it would appear to do so at a very localized level causing, perhaps, concentrations of water (and sediment) locally within a hillslope which in turn, influence local profile form. These effects may not be significant for the overall profile curvature of hillslopes which may reflect controls that operate at larger scales (e.g. climate and lithology)' (1979, 402). This finding of scale-dependence of a relation between profile and plan curvature is echoed in the Gara by the weak relation between the two for 50 and 100 m matrices with G, compared with that obtained from field measurements using 5 m gsl's.

5.4 Computer profiles from matrices : comparisons with fieldwork

i. Accuracy of field data

The data from the field must be treated with some caution : for a start, not all profiles are complete (see table 2.2). Another caveat is that the instruments used in field data collection were not chosen to yield great accuracy : thus bearings read with a prismatic compass and gsl's measured by stretching lengths of tape over the ground could cumulate error over a long profile to the extent that, in the extreme case, the horizontal position of the triangulation pillar at the crest of profile 19 as estimated by profile survey was 92 m away from its map position. This represents 10.51% of the total distance

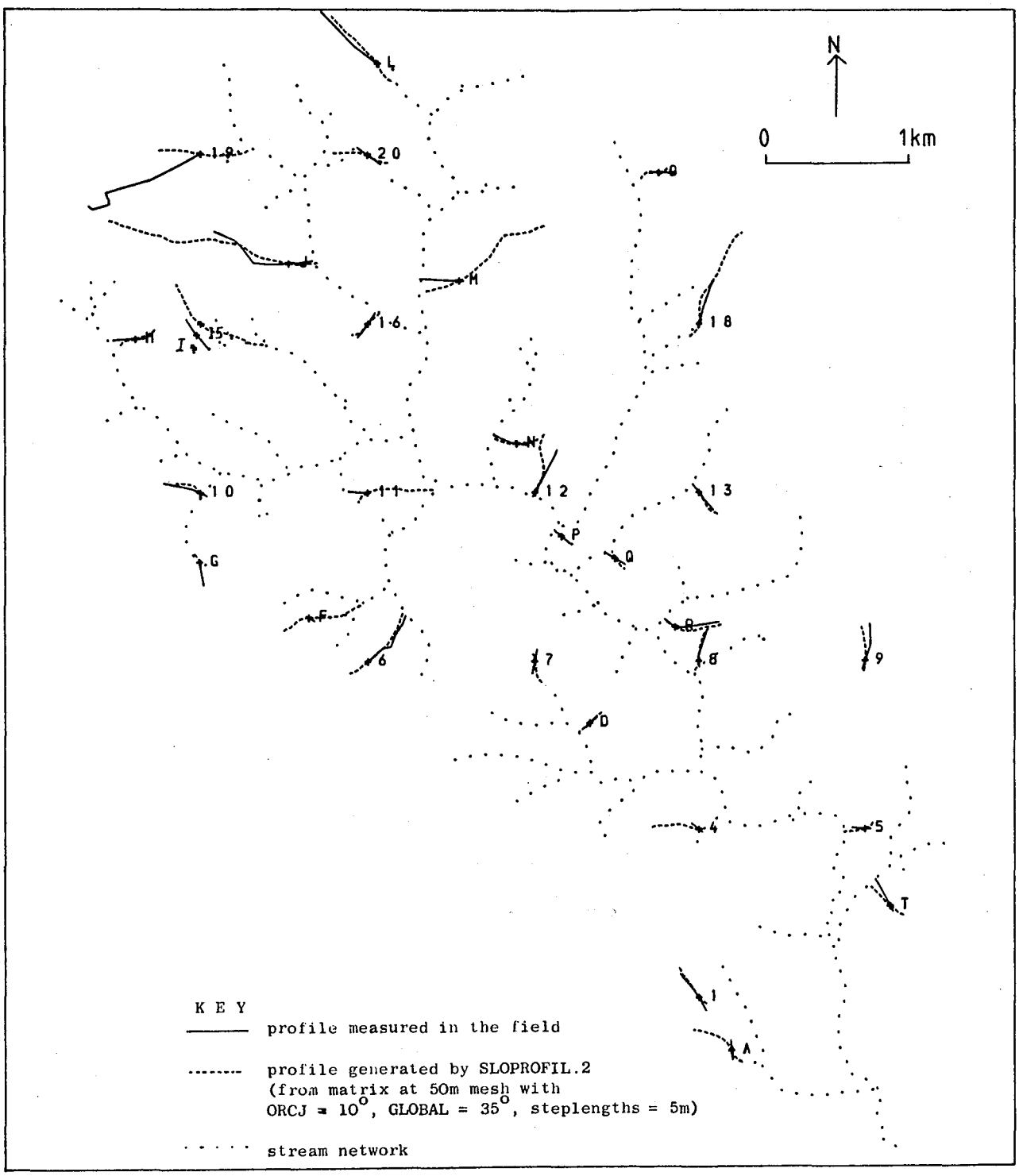
surveyed for a profile that had to traverse several field boundaries and a road. This magnitude of error is comparable with the larger difference in plan position quoted in section 4.5 for upslope compared with downslope tracing with SLOPROFIL.2 for a profile curved in plan.

Greater accuracy could undoubtedly be achieved in the field if theodolite and electromagnetic distance measurement (EDM) were employed, but at the expense of time and the ability of a geomorphologist to carry out survey alone; the BGRG Technical Bulletin (Young, 1974) sensibly argues that instruments like the clinometer, ranging pole and tape combination used here are adequate for most profile surveys. This adequacy is borne out by the figure for vertical error of the same triangulation pillar, as estimated by extrapolating from the (map-derived) height at the point of origin of profile 19 using known gsl's and angle measurements from field survey : the survey underestimated the pillar's height above datum by only 1m, which represents an error of 1.91% for the height range covered by the profile. Sampling errors (e.g. arising from slight misidentification of a profile point of origin) are likely to give rise to at least as large an error as this value for measurement error.

5.4ii Fidelity in path followed (map position of profiles)

Figure 5.4 shows that several field and SLOPROFIL.2-generated profiles agree well in plan position. Some discrepancies and correspondences deserve mention in the light of decisions made in the field and discussed in chapter 2.

Thus profile 11 generated from the matrix descends in the opposite direction to the field-surveyed profile 11, and finishes up near the trunk stream of the Gara at its downslope end, whereas the field-surveyed profile ended in a small tributary valley. It was stated in chapter 2



+1 points of origin for both profile sets, with label (numeric for grid scheme, alphabetic for PSBL)

Figure 5.4 : Map showing paths of profiles measured in the field, and generated on computer, using the same points of origin in the Gara catchment.

that difficulty was encountered in the field in deciding on the path of this profile from a point of origin in the middle of a flat summit; in view of this uncertainty it is impossible to say that the field or matrix-derived profile is 'correct', since the first involved some margin of error depending on how accurately the point of origin had been located in the field, and the second was dependent on manually-determined heights from the Ordnance Survey 1:10,560 maps at vertices, for which there was difficulty in deciding the values on a flat summit (chapter 3).

A second discrepancy occurs for profile G, which was also mentioned in chapter 2 because its point of origin fell on a stream. The matrix-derived profile follows the stream; the field profile takes a path upslope from the stream, as is accepted practice in profiling. Since the matrix does not 'know' that there is a stream there, this occurrence is not surprising; usually a computer-generated profile would stop at a stream because to follow it would require a large orientation change which it was programmed not to allow (chapter 4), but in the case of profiles G and F, the initial orientation change involved in following the talweg was not large.

In general the performance of the computer-generated profiles near to and along the streams is encouraging, since this is a potentially sensitive situation : with matrix points spaced at 50 m distance from each other, vertices are unlikely to fall exactly on the lowest point of the valley floor, and so there may be a margin of uncertainty as to the position of the talweg. The results suggest that the fitting of quadratics to the vertex data in SLOPROFIL.2 allows adequate representation of reality here. Figure 5.5 shows the result of an exercise carried out to test the validity of talweg definition by SLOPROFIL.2 : profiles were traced downslope from points of origin situated on the talwegs of the Gara;

K E Y

..... blue line (stream) network digitized from 1:25,000 scale OS maps

——— profiles generated by SLOPROFIL.2 tracing downvalley from points of origin on the stream network, with ORCJ & GLOBAL set to 360°

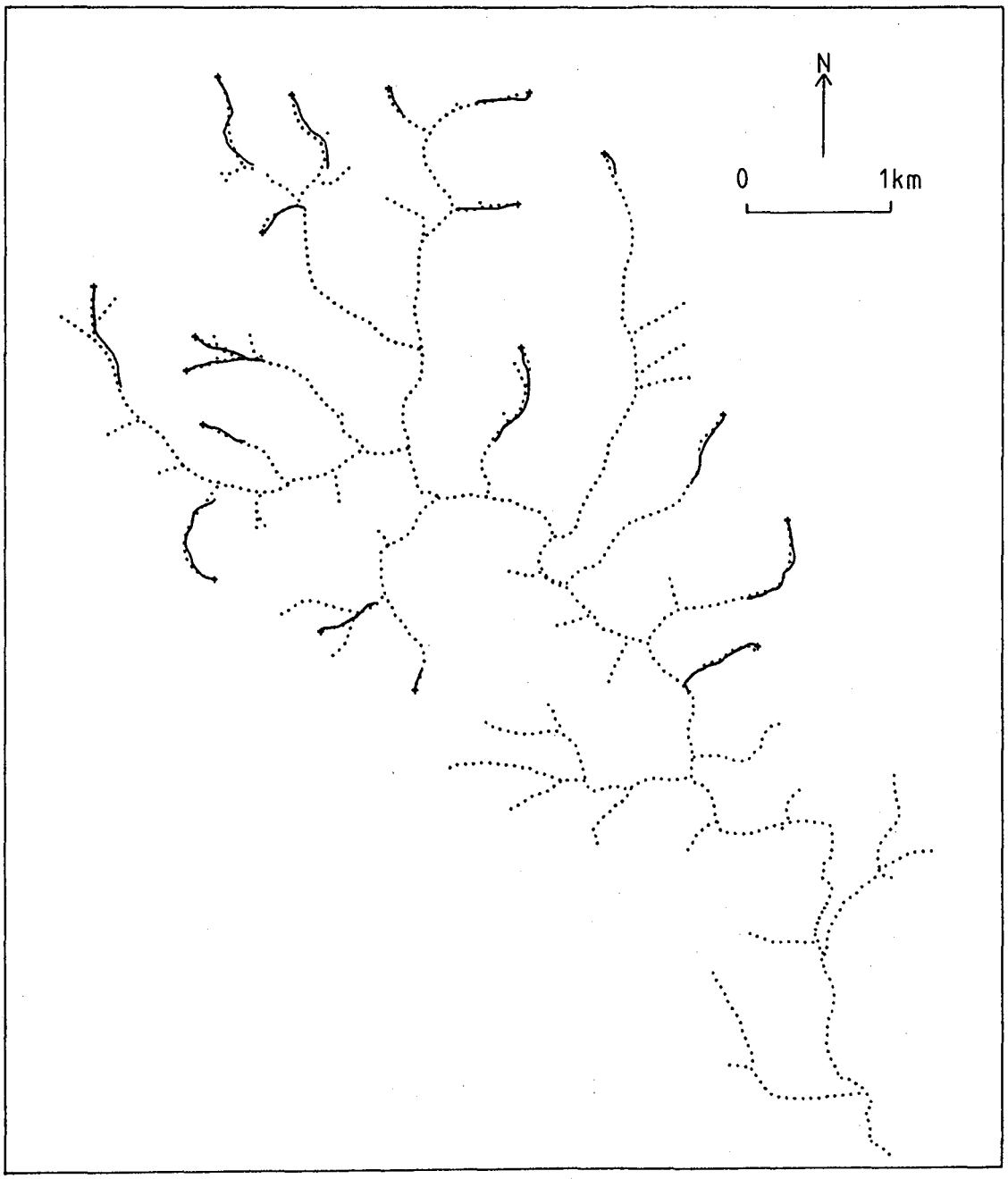


Figure 5.5 : Illustration of agreement between blue line stream network and paths of talwegs defined by SLOPROFIL.2 from Gara matrix at 50 m mesh.

the latter (defined from the blue line network on the 1:25,000 map) have been plotted with the profiles for comparison. The terminating variables ORCJ and GLOBAL were set to 360° for these profiles : if they had been set to low values, the profiles would have terminated after only a short distance as these talwegs swing through large bearings more often than do Gara hillslope profiles; termination was brought about by NHOPS (which controls the number of steplengths to be traced). The result shows that SLOPROFIL.2 is able to locate the talwegspretty accurately from 50 m mesh altitude matrix data.

The decisions taken in the field to terminate profile 1 at its downslope end in a small valley not marked on the map with a blue line to indicate a stream, but to terminate profile 6 at the blue line marked for its valley system despite its traversing a substantial concavity before this,are vindicated in the matrix-derived profiles : in both cases, field and computer profiles terminate downslope in the same place. Downslope termination by SLOPROFIL.2 for profile 1 (see table 5.3) was due to exceedance of the 35° limit on overall profile direction change : in the field it had been decided that to continue the profile below this point would lead to a change in direction of profile path by over 45°. For profile 6, downslope termination by SLOPROFIL.2 (table 5.3) was due to a local orientation change of over 10° : the computer profile had traversed the hillslope hollow upslope of this point without violating the 35°-overall or 10°-local thresholds for orientation change set; in the field it was judged that to continue profiling down this hollow would not violate the rule-of-thumb threshold at 45° orientation change used there. These two instances are encouraging confirmation that the tricky problem of profile termination is successfully resolved into questions of allowable orientation change in SLOPROFIL.2.

Table 5.3 : The reasons for termination of the computer profiles depicted in figure 5.4

Any reasons for premature termination of the field profiles in that figure are given in table 2.2

Profile name	Upslope end	Downslope end
A	2	2
D	1	1
F	2	1
G	1	1
H	2	2
I	2	1
J	3	1
L	3	2
M	2	6
N	2	1
O	2	2
P	2	6
Q	2	1
R	2	1
T	2	1
1	2	2
4	2	2
5	2	1
6	2	1
7	1	2
8	2	1
9	6	2
10	1	1
11	2	1
12	2	1
13	1	1
15	2	1
16	2	1
18	3	2
19	2	2
20	2	1

Key

1 local orientation change of over 10°
2 overall orientation change of profile by over 35°
3 edge of study area
6 reverse in sign of slope angle

Computer and field profiles R and 8 terminate upslope in similar positions, both due to violation of the overall bearing change limit of 35° (table 5.3). The upslope termination of these two profiles in the field was the subject of discussion in chapter 2 (andillustrated in figure 2.8); again, the successful reproduction of the field decisions by SLOPROFIL.2 acting according to consistent criteria for allowable orientation change, is an encouraging finding.

Another difficult situation in the field was that encountered at the points of origin of profiles I and 15, which fell in an area of ground with numerous channels. The solution decided on in the field (chapter 2) was to take a point of origin mid-way between the two, and survey the profile up towards higher land above the farm(where crops prevented further survey). In figure 5.4 the results of generating profiles from both starting-points can be seen, and it is clear that whereas profile I's point of origin fell in an area of confused topography from which it was not possible to sustain a profile along an approximately consistent bearing, it was possible to do this from profile 15's point of origin. These two points are 167 m apart, so the contrast indicates the importance of identifying points of origin in the field to well within that distance of their true positions.

Profiles J and 19 do follow rather different paths in the field and on computer; in this case it may be that the matrix profiles are more reliable, as it was difficult to decide on the path of true slope on this steady incline towards the highest part of the catchment, where field boundaries made it impossible to see the overall lie-of-the-land; note also the inaccuracy of triangulation pillar position at the crest of profile 19 as estimated by field survey, quoted in the previous sub-section.

Figure 5.4 illustrates the greater freedom of the computer-generated profiles to curve continuously in plan than was allowed for the field profiles, because of the time that would be involved in finding the bearing of true slope for every field-measured length and because a hummock could disturb the overall flow of the field profile if that was done. In this sense the computer profiles seem to be a success : because they are based on data at 50 m mesh, individual hummocks are smoothed out, yet the small steplength that can be used (e.g. 5 m horizontal intervals used to generate the profiles in figure 5.4) means that the profile is free to change orientation at frequent intervals to follow the curvature dictated by the quadratic surfaces. Figure 5.6 demonstrates this effect, showing that aspect of gsl's along true slope lines measured in the field is more concentrated along a few bearings than that for the computer profiles.

It can also be noticed on figure 5.4 that some computer profiles are markedly longer than their field equivalents. In some cases field profiles were terminated for reasons other than topography (e.g. because of crops - see table 2.2) so the field data are not ideal for fixing terminating conditions with SLOPROFIL.2. In chapters 6 and 7 experimentation with different values of terminating conditions in the program is discussed for the Gara, by comparison with statistics produced by G, since the goal of this research is to produce profiles to give reliable data on a landscape, not to replicate on the computer a field survey that was flawed.

5.4.iii Fidelity in shape (vertical section) of profiles

Figure 5.7 shows vertical plots of profiles N and L as measured by fieldwork and as generated by SLOPROFIL.2; it can be seen on figure 5.4 that these are two profiles for which agreement in plan position between field and computer profiles is good. The upper

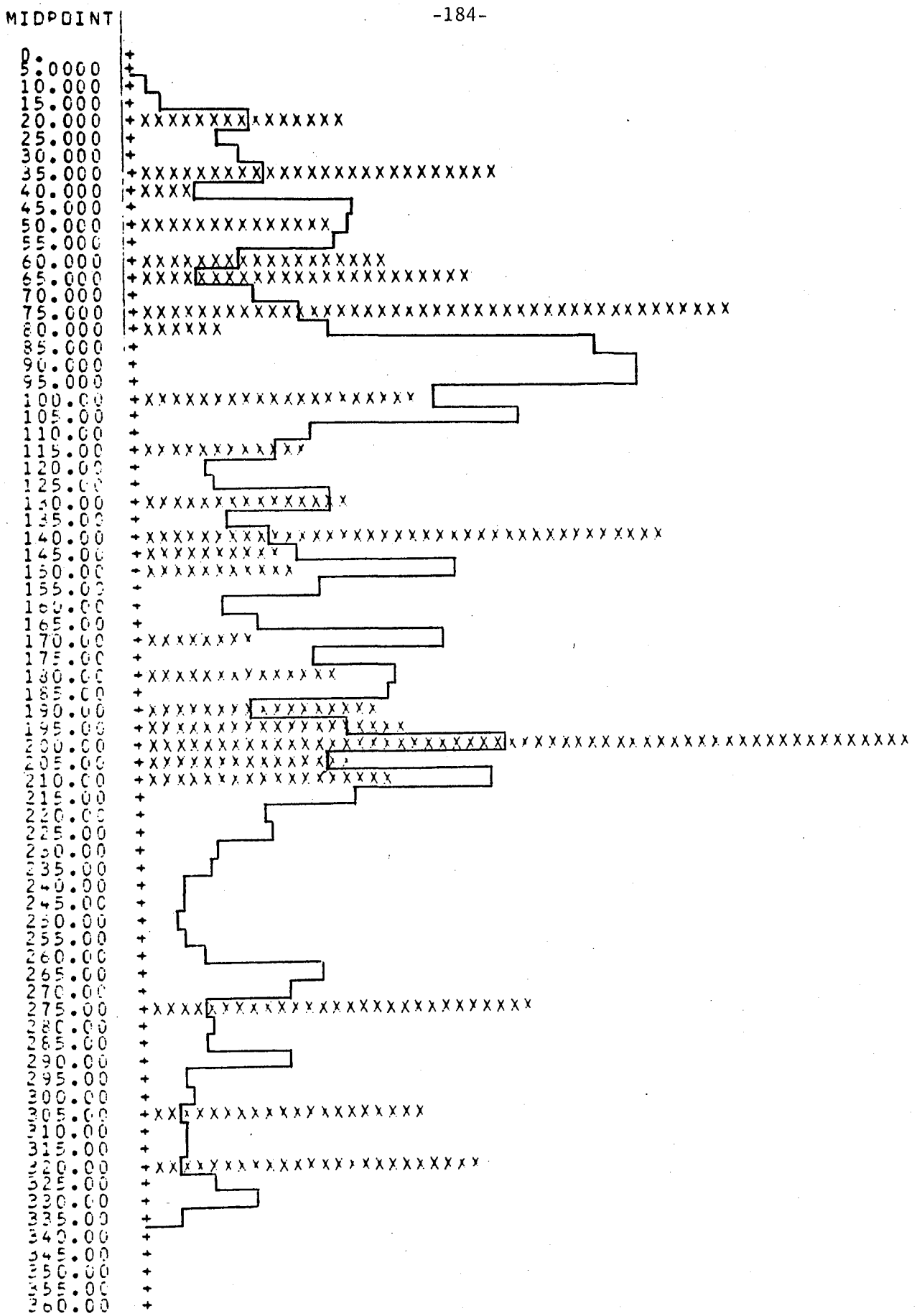
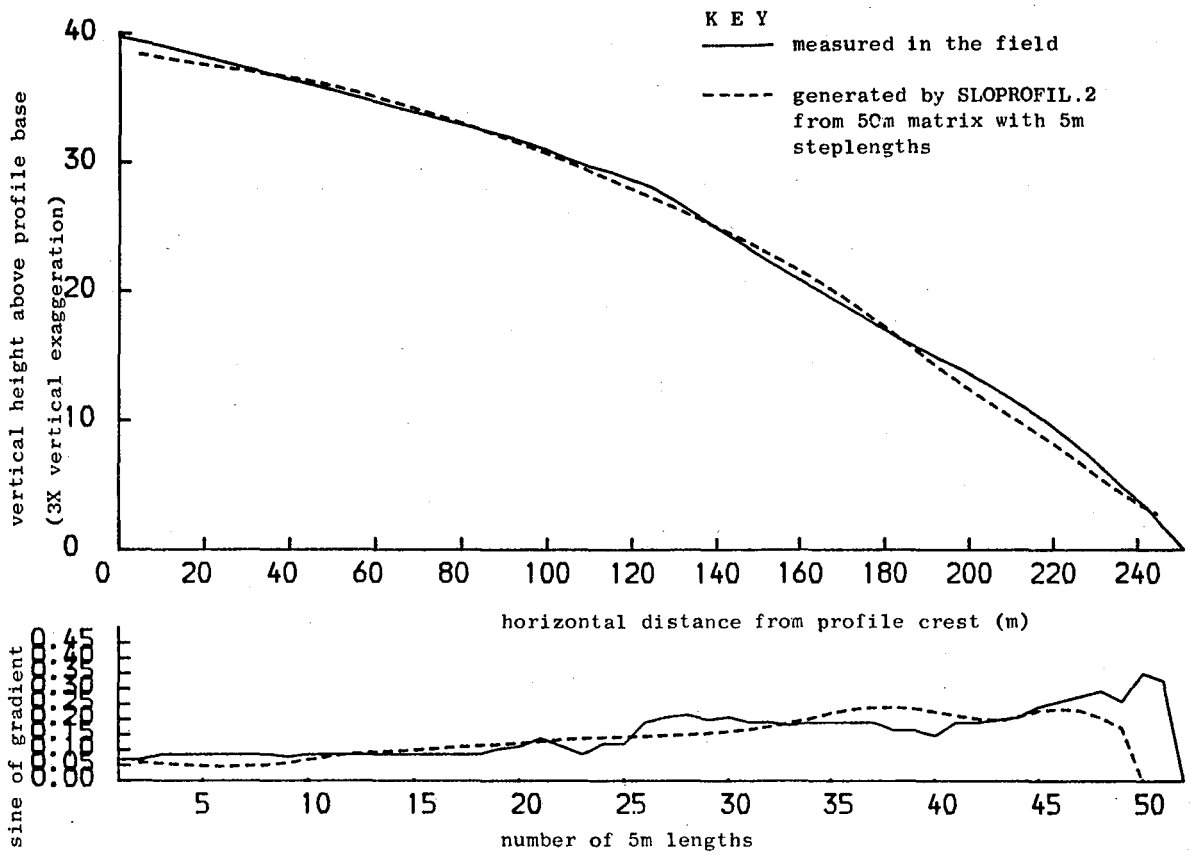
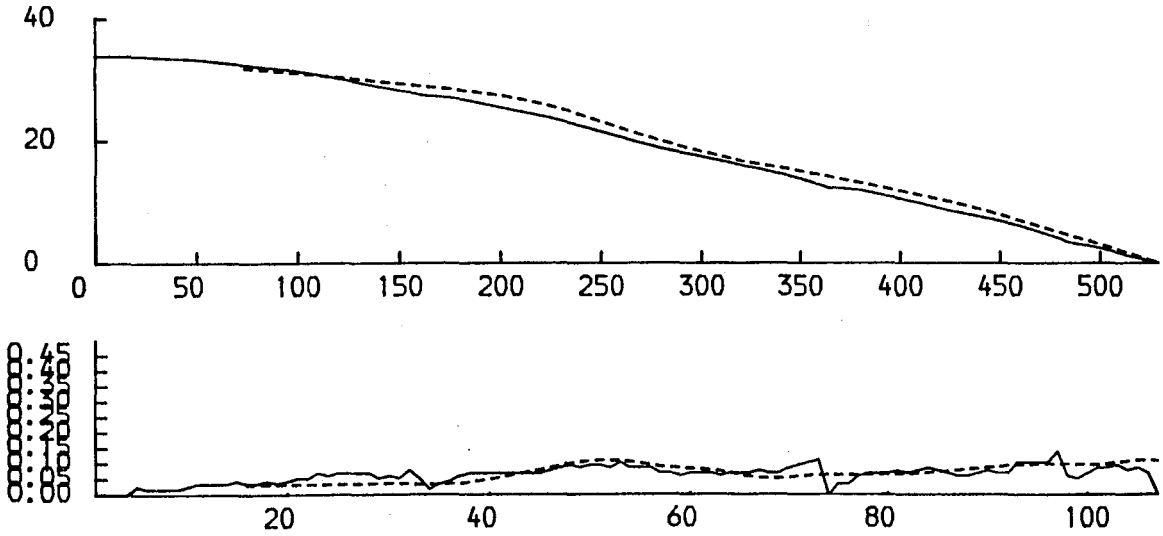


Figure 5.6 : Frequency distributions of aspect from field-surveyed and computer-generated profiles in Gara catchment.
Crosses (each X = 2) represent distribution from field survey with 5 m ground surface lengths; black-line boxes (same scale) refer to distribution from profiles generated by SLOPROFIL.2 from the 50 m matrix, with ORCJ=10°, GLOBAL=35° and steplengths= 5m.(Both are for the 16 profiles located by the grid scheme).



(A) Profile N



(B) Profile L

Figure 5.7 : Comparison of heights and gradients for two profiles in the Gara measured in the field and generated on computer.

plots of figures 5.7(A) and (B) show that computer and field profiles agree well in altitude in both cases; in the case of profile N, the computer profile underestimated the depth of the valley by about 3 m, which is not surprising when it is remembered that SLOPROFIL.2 is constructing a model of the landsurface from points spaced 50 m apart.

The lower plots in both cases show a comparison of field and computer-generated gradients along the profiles; it can be seen that the field profiles are more uneven in this respect. This difference is in some ways analogous to the matrix smoothing of plan (bearing) angularity that was noted in the previous sub-section. The latter was explained as being partly due to the method of measurement of field profiles (bearings only being allowed to change every 30 m), whereas the contrast in vertical section is likely to owe more to the contrast in detail of measurement resolution between field and matrix. As an illustration, it was quite usual for a step to be encountered in a field profile on the downslope side of a hedgerow, behind which soil had piled up over the years; such a feature is not recorded on the 1:10,560 map and therefore is absent from the matrix of the area. Such detailed-scale irregularities are the reason why there is a considerable difference between profile curvature as calculated by A.Young's formulae 1 and 2 for field measurements at 5 m gsl's; the absence of these features from the matrix means that the two methods of calculating profile curvature yield fairly similar results for computer-generated profiles (quoted in section 5.3).

5.4 iv <u>Similarity in gradient</u>

In order to investigate whether computer-generated profiles were <u>consistently</u> more subdued, or steeper, in gradient than field-measured profiles, the field data measured at 5 m gsl were interpolated to give the readings that might have been obtained had 5 m

horizontal constant distances been used, and then the same portions of field and computer profiles (the latter also for 5 m horizontal constant lengths) were compared. Pairing was undertaken for every length upslope and downslope of a point of origin for which both field and computer profiles had obtained a gradient reading, regardless of whether these profile paths agreed on figure 5.4, because it was necessary to see how similar gradient readings from field and computer survey could be, given that some differences in identification of true slope path would tend to occur in the two cases.

Figure 5.8 shows the distribution of residuals resulting from subtraction of computer profile gradient from field profile gradient (in degrees) for the same gsl's in the two kinds of dataset. It shows that the modal class is actually just on the negative side of zero, implying greater computer-generated than field gradients, although the longer tail on the distribution is towards high positive values (greater field than computer-generated gradient), showing that the matrix-derived data fail to reproduce the high extremes of gradient recorded in the field.

Figures 5.9 and 5.10 show in more detail how the differences between field and computer profile gradients are constituted, for two individual profiles, N and 16 (shown in figure 5.4). For profile N, plots (A) and (B) show that the distribution of computer gradients is more evenly spread over the range than are the field values : the latter are distinctly bimodal. The residuals (plot C) are most numerous between + and -1.9°, which is encouraging; the one large positive residual of 8.7° is due to the inability of the matrix to detect a river cliff. On figure 5.10, a wider spread of residuals is encountered (plot C) for profile 16. This is because computer and field profiles produced slightly different estimates of the position

```
MIDPOINT    HIST%   COUNT|
-12.500       .1       2 +X
-11.500       .2       3 +X
-10.500       .2       3 +X
-9.5000       .3       4 +XX
-8.5000       .6       9 +XXX
-7.5000      1.1      16 +XXXXXX
-6.5000      1.4      20 +XXXXXXX
-5.5000      2.4      34 +XXXXXXXXXXXX
-4.5000      3.5      50 +XXXXXXXXXXXXXXXXX
-3.5000      5.1      72 +XXXXXXXXXXXXXXXXXXXXXXXX
-2.5000      8.8     124 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-1.5000     12.6     178 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-.50000     14.5     205 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 .50000     12.2     172 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 1.5000     10.8     153 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 2.5000      8.1     114 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 3.5000      5.3      75 +XXXXXXXXXXXXXXXXXXXXXXXXX
 4.5000      3.2      45 +XXXXXXXXXXXXXXX
 5.5000      2.5      35 +XXXXXXXXXXXX
 6.5000      1.5      21 +XXXXXXX
 7.5000      1.4      20 +XXXXXXX
 8.5000      1.2      17 +XXXXXX
 9.5000       .7      10 +XXXX
 10.500       .8      11 +XXXX
 11.500       .3       4 +XX
 12.500       .4       6 +XX
 13.500       .3       4 +XX
 14.500       .3       4 +XX
 15.500       .1       2 +X
 16.500       .1       1 +X
```

Figure 5.8 : Residuals plot created by taking SLOPROFIL.2 gradients away from field gradients (both in degrees measured over 5 m horizontal lengths) for 30 profiles
Each X = 3.

	2 .	788
	3 .	003344
500	4 .	06
2100000000000000	5 .	1468
640	6 .	1469
950	7 .	148
	8 .	023467
551	9 .	0379
965	10 .	29
8762100000	11 .	3789
931	12 .	138
	13 .	02256699
5	14 .	
85	15 .	
6	16 .	
	17 .	
6	18 .	

A) measured in the field B) generated on computer

	-4 .	45
	-3 .	45
	-2 .	58
	-1 .	1234458
	-0 .	1345678889
	0 .	4456778
	1 .	013379
	2 .	00223567
	3 .	4569
	4 .	
	5 .	
	6 .	
	7 .	
	8 .	7

C) residuals created by taking computer gradients from field

Figure 5.9 : Stem-and-leaf plots showing statistical comparison between gradients for the same 5 m lengths measured in the field and generated on computer for Gara profile N.

5000	2 .	
000	3 .	69
500	4 .	123357
	5 .	147
	6 .	049
665440	7 .	48
41	8 .	2579
21	9 .	123347
2	10 .	229
960	11 .	8
4320	12 .	25
76332100	13 .	178
90	14 .	39
	15 .	0467
610	16 .	

A) measured in the field B) generated on computer

	-7 .	266
	-6 .	2
	-5 .	2
	-4 .	8
	-3 .	
	-2 .	26
	-1 .	0133456669
	-0 .	2
	0 .	001
	1 .	1333358
	2 .	367
	3 .	569
	4 .	
	5 .	34
	6 .	4
	7 .	
	8 .	346

C) residuals created by taking computer gradients from field

Figure 5.10 : Stem-and-leaf plots showing statistical comparison between gradients for the same 5 m lengths measured in the field and generated on computer for Gara profile 16.

of a marked steepening in the profile, although this steepening was present on both types of profile. This is why the residuals are fairly evenly distributed either side of the zero mark. This difference could be due to error in the field in locating the profile point of origin exactly, or to a genuine difference between the field slope and that modelled by the matrix; the residuals plot shows that the computer profile is an unbiased estimator of field profile gradient, at least.

The residuals in figure 5.8, obtained from the whole sample of field and computer profiles, also show an encouraging lack of bias (i.e. low skewness). This is evidence that profiles generated by SLOPROFIL.2 are not consistently under- or over-estimating reality. Although some large residuals have been produced, 67% of the residuals are within $\pm 3°$ of 0°.

5.5 Concluding remarks

The first part of this chapter (section 5.3) demonstrated some effects of scale and method of measurement, which cause land form measures derived from a matrix at 50 m mesh to depart from those measured in the field by profiling with 5 m gsl's. It was shown that the dampening influence of the coarser scale of measurement of the matrix was partly counterbalanced, especially for gradient statistics, by taking derivatives of a quadratic surface in program G rather than discretizing the surface as a series of straight lines as is the case in the profiling method.

The second part (section 5.4) has demonstrated the acceptability of profiles derived from matrices using SLOPROFIL.2, by selected comparisons with the same profiles measured in the field. Further overall statistical comparisons between field and computer profile data are reserved for the next chapter where statistics from computer-generated

profiles are discussed in the course of an examination of terminating conditions for such profiles; the latter are best fixed by reference to matrix-G results.

This chapter has shown, not surprisingly, that map-derived distributions of land form attributes are more smoothed than those measurable in the field. However this does not prevent map data at 1:10,560 scale from yielding contour orthogonals similar to those that can be measured in the field. This latter is the important finding : it is not an aim of this study to demonstrate that matrix studies can replicate and therefore supplant fieldwork for a geomorphological exercise, but rather to enable extensive experimentation to be carried out with sampling strategies on computer (with SLOPROFIL.2) before fieldwork, so that the latter may be executed with maximum speed and accuracy. It might be argued that populations of attributes measurable in the field are different from those from the map, so that one cannot be used to predict an unbiased sample of the other. This research disputes that this is the case for altitude and gradient (evidence for this is presented in sections 5.3 i and 5.4 iv), as well as aspect (evidence comes from agreement between field and map-derived profile paths, figure 5.4). It may however be more appropriate to say that profile curvature is quite different at the 5 m scale in the field, as is indicated by its contrasting characteristics at local and at more reconnaissance scales, illustrated in section 5.3ii.

Maps at the most detailed commonly-available scales (Ordnance Survey 1:10,560) therefore do pick out the main topographic features followed by a contour orthogonal, while fieldwork fleshes these out with additional measurement of more local land surface fluctuations due to small-scale relief, hedgerows, and the like. Although the extremes of field and map-derived attribute distributions may be very

dissimilar (which is why this research attaches little importance to comparisons of maxima and minima of attributes), the central tendencies are not. Having established this broad correspondence between field- and map-derived slopes, it is meaningful to compare map-derived attributes from G with those from SLOPROFIL.2 on the assumption that findings from these comparisons will have relevance for field profiling.

5.6 Notation

β local gradient (measured over one ground surface length)

C profile curvature attributable to a measured length, in degrees per 100 m

D length of ground surface measurement

n number of the ground surface length in a profile. (Numbering starts at the profile crest)

S profile curvature attributable to a profile station, in degrees per 100 m

CHAPTER 6 : EXPERIMENTATION WITH COMPUTER PROFILE LENGTHS AND SAMPLING PATTERNS IN THE GARA CATCHMENT

6.1 Introduction

6.2 SLOPROFIL.2 : some general points

6.3 Choice of profile lengths on computer for the best field survey

i. Introductory

ii. Gradient

iii. Profile curvature

iv. Altitude

v. Conclusions

6.4 Spatial coverage of profiles from different sampling schemes

i. Introductory

ii. Profile sampling baseline scheme

iii. Grid sampling scheme

iv. Stream and divide scheme

6.5 Conclusions

6.1 Introduction

In chapter 5 the agreement between profiles constructed from matrix information using SLOPROFIL.2 and field-measured profiles was investigated. It was found that agreement was good in the Gara catchment : most matrix-based profiles followed similar paths to field-measured ones and did not consistently over- or under-estimate field gradients. Section 5.3, however, showed that some characteristics of frequency distributions of land form attributes measurable in the field with 5 m ground surface lengths (gsl's) could not be reproduced with 50 m matrix data from 1:10,560 scale maps. A process study in geomorphology requiring detailed topographic measurements over an area will usually need an additional field survey, if the worker opts to construct a reconnaissance-scale altitude matrix as was the case for the Gara. The design of this field survey can however be formulated on the computer from matrix information before fieldwork, in a way to be demonstrated by this research.

In this study the sequence of operations was not carried out in the order recommended above, because field profiles were needed first to ascertain the success of the newly-constructed SLOPROFIL.2 algorithm in representing field profiles. In this present chapter more analyses are carried out which would not need to be performed by a geomorphologist following this approach, but are necessary here to demonstrate how best to proceed.

In the third section of this chapter results are reported from generation of profiles on computer starting from the points of origin used in the field survey of the Gara catchment. Experimentation is carried out with different values of the terminating variables in SLOPROFIL.2 in an attempt to reproduce the statistics output from analysis of the matrix with program G, which provides coverage of all

terrain types in the catchment. The results presented in section 6.3 are important for the sensitivity of summary statistics of land form attributes to profile length demonstrated.

In the fourth section, large numbers of profiles are generated by SLOPROFIL.2 according to different schemes for locating profile points of origin, in order to indicate which scheme gives the most complete areal coverage of profiles. The freedom to investigate the outcome of large profile samples has never been available to field profilers because of the prohibitive amounts of time needed to collect such information by field survey. SLOPROFIL.2 can be used to produce limitless numbers of profiles on a surface, however. If coverage of a surface by a set of profiles does not become more complete and more even as the number of profiles is increased, it is assumed that the scheme generating such profiles is biased in its sampling of the surface.

6.2 SLOPROFIL.2 : some general points

Land form properties from G and from SLOPROFIL.2 are both derived from quadratic surfaces fitted by least squares to altitude matrix information at the same grid mesh. Therefore, when summary statistics are compared, the systematic sample of information from G can act as an indication of the coverage of the land surface being achieved by matrix-based profiles. A minor difference between the two is that for SLOPROFIL.2, the gradient data used are calculated for the inclination of lines separating consecutive profile stations on a contour orthogonal, whereas G's gradients are for derivatives. Agreement between inclined line and derivative measurements has been shown to be good (section 5.3) when small steplengths are being used in SLOPROFIL.2, as is the case in section 6.3 where 5 m horizontal lengths are used.

This length is almost identical to that used in fieldwork in the Gara (5 m measured along the ground surface), following the recommendation of BGRG Technical Bulletin 11 (Young, 1974). However the issue of sampling resolution recurs throughout the analyses of results in this chapter and the next, and the matter is investigated in its own right in chapter 8.

Profile curvatures in SLOPROFIL.2 are found by applying Young's formula 1 (quoted in section 5.3) to three consecutive gsl's, whereas those in G are second derivatives. Second derivatives were not calculated in SLOPROFIL.2 because the final squares fitted by Jancaitis and Junkins' weighting function ensure continuity across boundaries only in first order derivatives (section 4.4). For the same reason, no estimation of plan curvature has been made for matrix-based profiles. If this was of importance to a study it could be made possible by using a weighting function of higher order in fitting final surfaces in subroutine JNJFIT of SLOPROFIL.2 (see Jancaitis and Junkins, 1973, 36; also in Junkins, Miller and Jancaitis, 1973, 1798). Young's formula 1 has been found to underestimate standard deviation of profile curvature as a second derivative (approximated by use of Young's formula 2) by about 5% for matrix-based profile data at 5 m steplengths (quoted in section 5.3).

A final and possibly more fundamental source of difference between land surface attributes from G and from SLOPROFIL.2 is the fact that the latter must ensure the fitting of a continuous surface by using the Jancaitis and Junkins weighting function, whereas the former can rely on quadratics alone because the sampling is point- rather than line-based. This matter is investigated in chapter 8.

The parameters that can be varied in SLOPROFIL.2 to give different lengths of profile output are

(1) ORCJ (ORientation Change), the maximum change in bearing allowed between two successive gsl's (see figure 6.1);

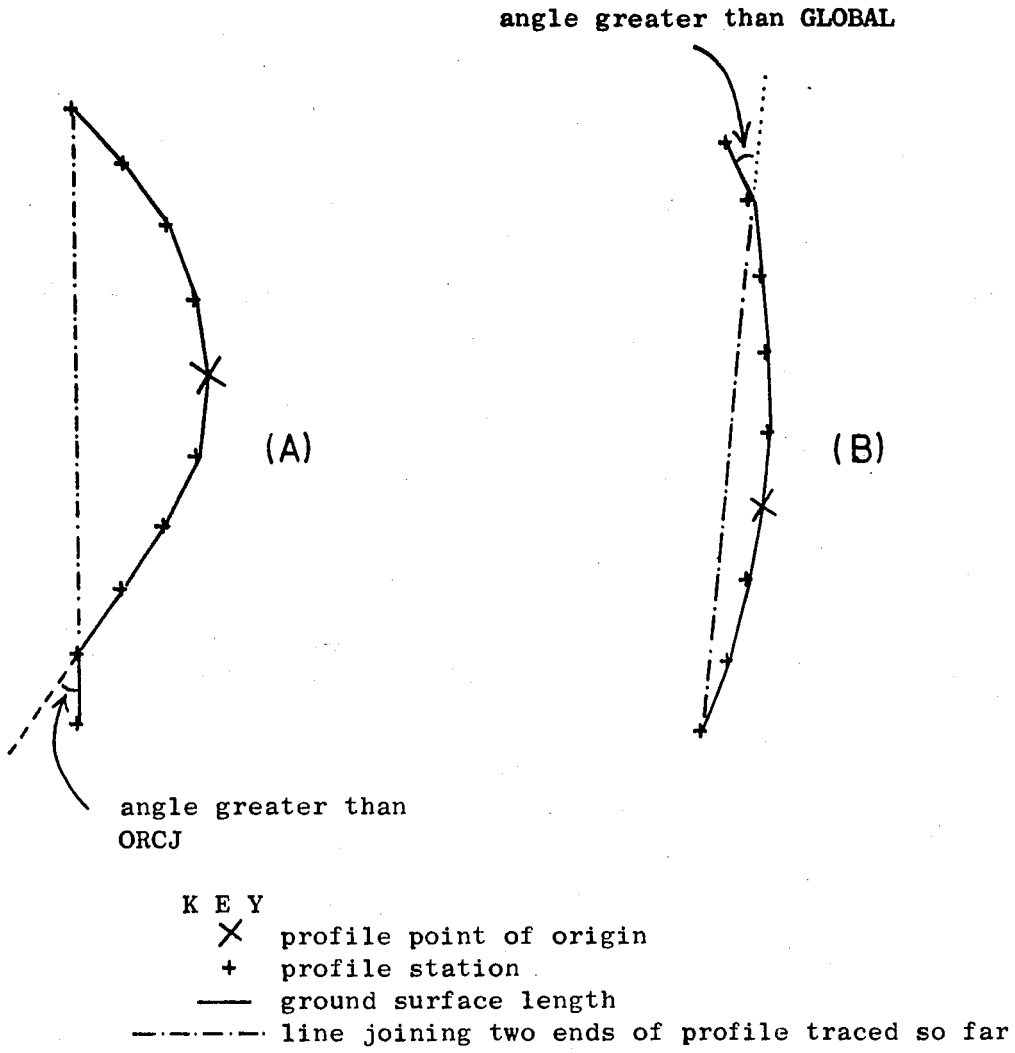


Figure 6.1 : Plan drawing of two profiles in diagrammatic form, to illustrate terminating conditions connected with variables (A) ORCJ and (B) GLOBAL in SLOPROFIL.2.

(2) GLOBAL, a comparison of the bearing of a new gsl with that of the whole profile as it has been traced so far. If the two differ by more than GLOBAL degrees, that gsl is not included in the profile and termination is brought about for that end of the profile (see figure 6.1); and

(3) NHOPS, the number of points to be traced up- and downslope from (and including) the starting-point. e.g. a value of NHOPS = 20 would allow a profile 19 + 19 = 38 gsl's long. If it is not to contribute to termination, this variable can be assigned a large value such as 9999 (the size of the dimensioned arrays to hold values of quantitative attributes of each gsl in SLOPROFIL.2) ,which would allow a profile with 19996 gsl's to be traced. This was the case in all the runs described in the following section : the longest profile to be generated in this set of runs was 319 gsl's long.

6.3 Choice of profile lengths on computer for the best field survey

i. Introduction

The question being addressed in this section is : given the number and positioning of points of origin of field-surveyed profiles in the Gara catchment, how near can matrix-based profiles extended from these points come to yielding the values of summary statistics of land form attributes obtained from the matrix with G?

In the Gara, acceptable profiles could usually be produced if ORCJ was set to a value sufficiently large (e.g. 360°) that it did not in practice contribute to termination at all. When it was set at a small value (e.g. 10°), it brought about termination downslope more often than upslope, because at the downslope end a sudden orientation change of true slope path is often encountered at the junction between slope

foot and talweg : witness the observation during field survey that downslope termination decisions were relatively easy. If ORCJ was set to a permissively high level, however, GLOBAL (e.g. set to 35°) would bring about termination near these locations anyway. The main use for ORCJ in practice was in stopping profiles, such as F and G, with points of origin on or near a talweg, from continuing on down the valley : ORCJ's sensitivity to talweg-following must be because these valley floors wander more in plan than do hillslope orthogonals. In any case, it is not desirable to allow profiles to follow talwegs, and for this reason ORCJ was kept at a satisfactory value of 10°.

Profile lengths were very sensitive to the value of GLOBAL chosen, as can be seen by comparing figures 6.2 and 6.3, which illustrate matrix-based profiles resulting from a generous value of GLOBAL (65°) and a restrictive value (15°) respectively. A visual comparison is helpful but not sufficient : table 6.1 shows the variation in selected summary statistics of the chosen land form attributes as the value of GLOBAL (and hence profile length, indicated in the right-hand column of the table) is increased. Sensitivity to the value of GLOBAL used in computer profile termination will be discussed below for the land form attributes in turn.

6.3ii. Gradient

Mean gradient (column 4, table 6.1) stands out as a useful discriminator between samples as it decreases steadily with increasing GLOBAL for grid and PSBL schemes, because as profiles get longer, greater coverage of crestal areas with low gradients is responsible for reducing the figure (compare figures 6.2 and 6.3). The variation of this statistic is portrayed graphically in figure 6.4, which makes clearer the fact that there are differences between estimates of it by PSBL and grid schemes for the same value of GLOBAL. For lower values of

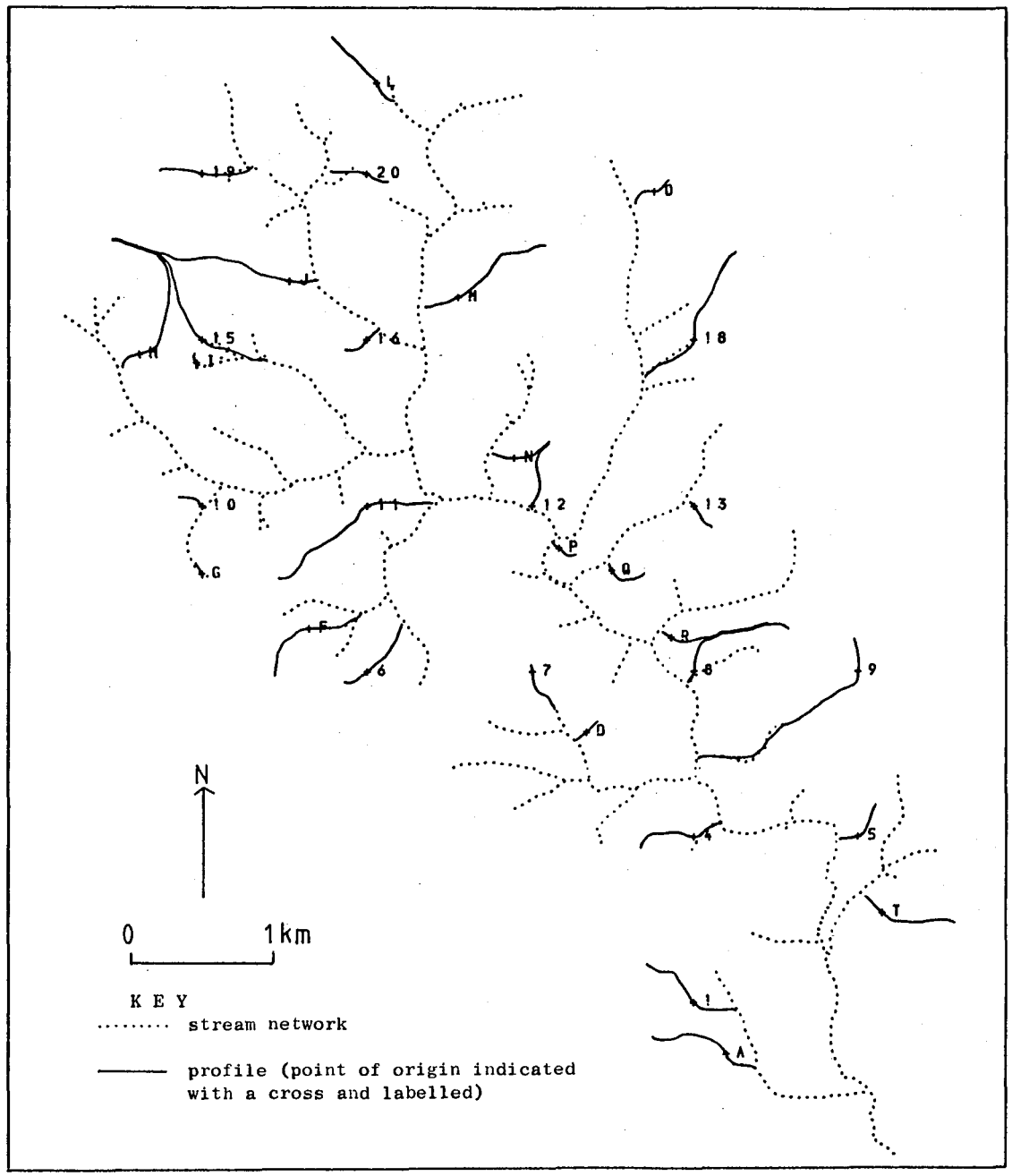


Figure 6.2 : Computer profiles generated from grid and PSBL points of origin used in fieldwork, with ORCJ = 10°, GLOBAL = 65° and steplengths= 5 m .

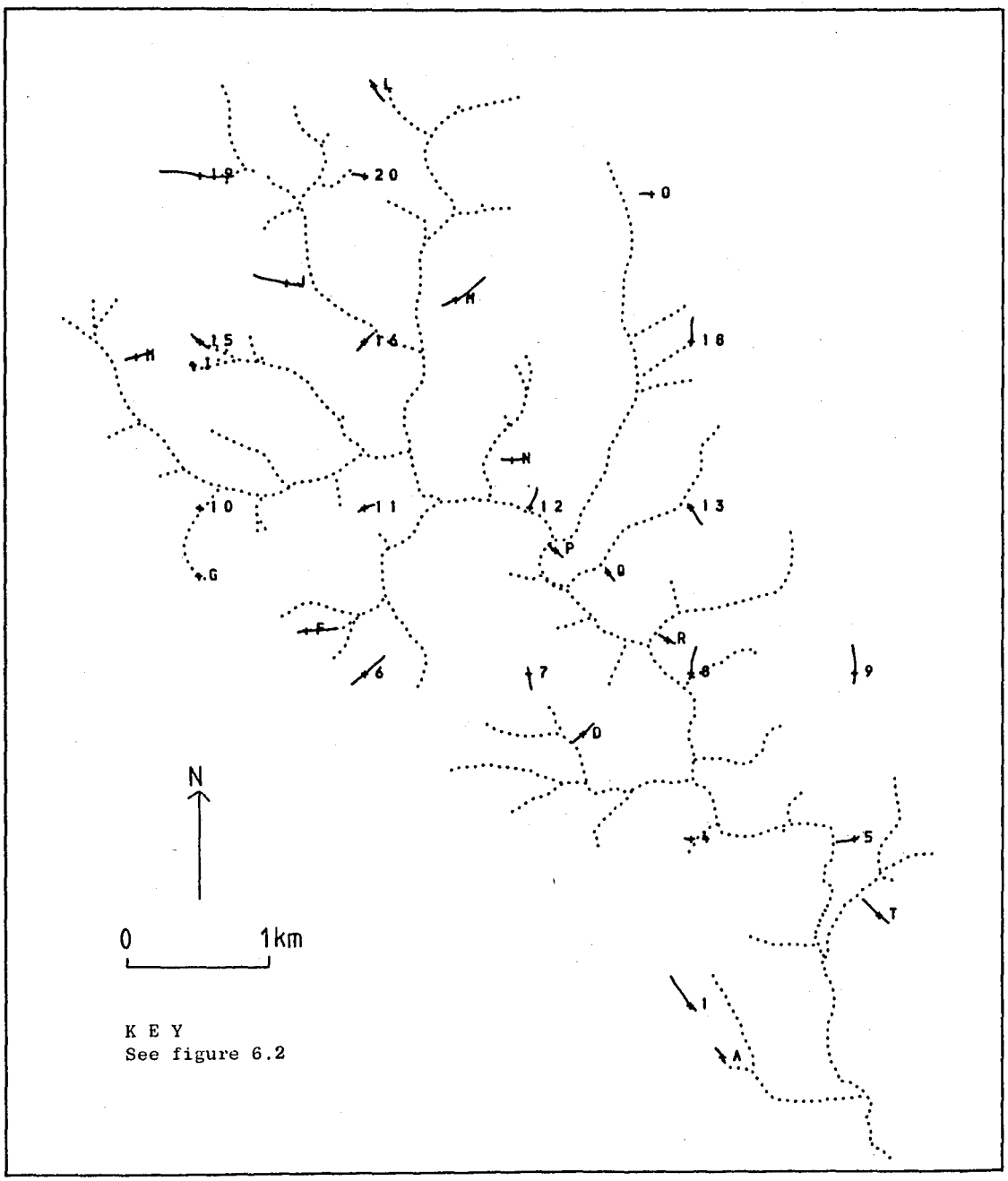


Figure 6.3 : Computer profiles generated from grid and PSBL points of origin used in fieldwork, with ORCJ = 10°, GLOBAL = 15° and steplengths = 5 m .

Table 6.1 : Summary statistics of land form attributes for matrix-G , field profiles, and profiles generated by SLOPROFIL.2 with different values of GLOBAL. (All PSBL samples no. of profiles = 15, all grid samples no. = 16)

Sampling scheme (value of GLOBAL indicated in brackets, where appropriate)	ALTITUDE (m)			GRADIENT (°)			PROF. CURV (°/100m)		Correlation altitude/ gradient	Average profile length in m (measured horizontally)
	mean	st.dev.	skew	mean	st.dev.	skew	st.dev.	skew		
50m matrix	120.62	39.56	-0.40	7.40	4.55	1.16	9.62	-1.87	-0.49	
field psbl	122.00	40.33	-0.15	8.14	5.90	1.16	23.77	-0.39	-0.65	261.64
field grid	131.94	40.59	0.26	7.78	5.45	1.05	23.26	-0.23	-0.60	290.29
psbl (15°)	116.20	33.35	-0.52	9.57	5.18	0.98	13.18	-0.90	-0.57	183.00
grid (15°)	122.83	35.95	-0.65	8.44	4.88	1.24	11.33	-1.47	-0.64	200.94
psbl (25°)	121.52	36.25	-0.12	8.62	4.91	1.11	13.53	-0.99	-0.61	271.33
grid (25°)	123.44	34.32	-0.45	7.77	4.50	1.22	10.66	-1.47	-0.52	312.50
psbl (30°)	134.49	42.63	-0.03	7.41	4.81	1.28	12.60	-1.68	-0.66	365.33
grid (30°)	129.64	36.69	-0.25	6.98	4.42	1.31	10.02	-1.38	-0.55	401.88
psbl (35°)	137.65	43.16	-0.10	6.80	4.76	1.35	11.85	-1.84	-0.64	426.33
grid (35°)	124.20	33.65	-0.28	6.84	4.37	1.33	10.07	-1.34	-0.47	425.00
psbl (45°)	137.02	42.00	-0.15	6.13	4.58	1.45	10.92	-1.76	-0.55	550.67
grid (45°)	126.87	38.06	0.14	6.29	4.29	1.36	9.42	-1.53	-0.51	589.06
psbl (65°)	137.38	41.37	-0.14	5.81	4.49	1.55	10.61	-1.63	-0.52	605.33
grid (65°)	121.93	37.73	0.27	5.63	4.16	1.51	9.03	-1.49	-0.37	735.31
	figures underlined are those closest to the matrix-G result either for PSBL or for grid sampling with SLOPROFIL.2									figures underlined are those closest to field results

Note: steplengths used in all computer-generated profiles are 5 m measured horizontally; lengths used in all field profiles are 5 m measured along the ground.

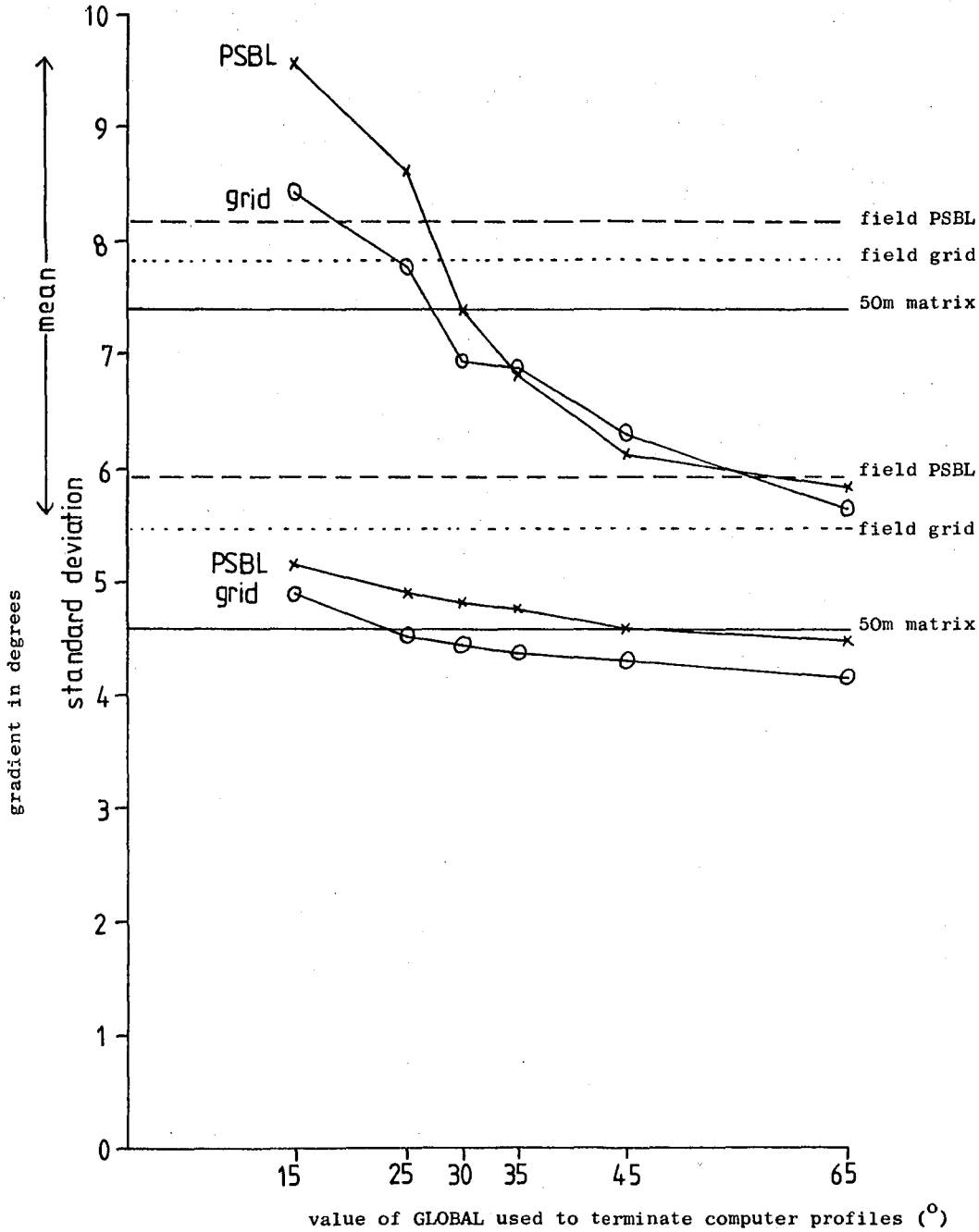


Figure 6.4 : Graph showing variation of mean and standard deviation of gradient for field profiles generated on computer with different values of GLOBAL.

GLOBAL (15, 25, 30°) the grid profiles give a lower mean gradient than the PSBL, which is consistent with the field results. This is because PSBL profiles are not sampling as much of the summit areas since too large an orientation change is required to get many of them out of the valley areas where they all start, by contrast with the grid scheme profiles some of which start on crestal areas. For GLOBAL = 35° and over, PSBL and grid scheme mean gradients are more similar, suggesting that differences in sampling coverage by the two schemes become less important - as far as this statistic is concerned - once the orientation change allowed to PSBL profiles enables them to reach flatter summit areas.

Standard deviation of gradient also declines with increasing GLOBAL (figure 6.4), the figure being consistently lower for grid than for PSBL samples, because the former involves less sampling of steep valleyside gradients. The evidence from mean gradient suggests that a grid sample with GLOBAL $\approx$ 27°, or PSBL with GLOBAL = 30°, gives coverage most like matrix-G's; standard deviation of gradient again favours the grid scheme with GLOBAL = 25°, but the PSBL scheme does not come into line until GLOBAL = 45°.

Estimation of mean gradient by grid survey in the field is .38° greater than that from matrix-G; that by the field PSBL survey is .74° greater. Given the steep decline of mean gradient for the PSBL scheme as GLOBAL increases from a low value (figure 6.4), this error in estimation by field PSBL survey was inevitable for the relatively short mean length of field-measured PSBL profile at 262 m. This sensitivity of results to length of profile surveyed is an important disadvantage of the PSBL scheme. Standard deviation estimated by both field survey schemes is in excess of any produced by a matrix-based profile sample; this owes much to variability in the field not captured by the map and matrix, as has already been explained in chapter 5.

Skewness of gradient is well estimated by matrix-based profiles around the GLOBAL = 25° mark; increasing positive skewness for GLOBAL values greater than these indicates more extensive coverage of low-angled summits.

6.3iii Profile curvature

The variation of standard deviation and skewness of profile curvature for different values of GLOBAL for the two sampling schemes is shown in figure 6.5 (mean figures for curvature are not presented here as they are usually around zero and not as revealing as the other two measures). The difference between the estimation of standard deviation of profile curvature by grid and PSBL methods is striking : as with standard deviation of gradient, the PSBL values are consistently greater than the grid ones for the same GLOBAL. However in this case, the matrix-G value agrees with the grid value for GLOBAL = 35 - 45°, but is much overestimated by the PSBL scheme even for GLOBAL = 65°. Since it was suggested when discussing gradient statistics that grid scheme GLOBAL≈27° and PSBL scheme GLOBAL≈30° made for best agreement with matrix-G statistics, there would seem to be a discrepancy to be explained here. This discrepancy cannot be explained by the different ways of calculating profile curvature from SLOPROFIL.2 data and in G, because this has been shown to cause slight underestimation rather than overestimation of this attribute by SLOPROFIL.2 (section 5.3).

Figure 6.6 provides more background information on this question. Presented on the left-hand side of both stem-and-leaf plots of that figure are gradient and profile curvature calculated as a first and second derivative respectively by G, for the vertices defining two neighbouring unit square areas (50 m x 50 m) in the Gara matrix. On the right-hand side of the plots, gradient and profile curvature are presented from a segment of profile traced by SLOPROFIL.2 approximately

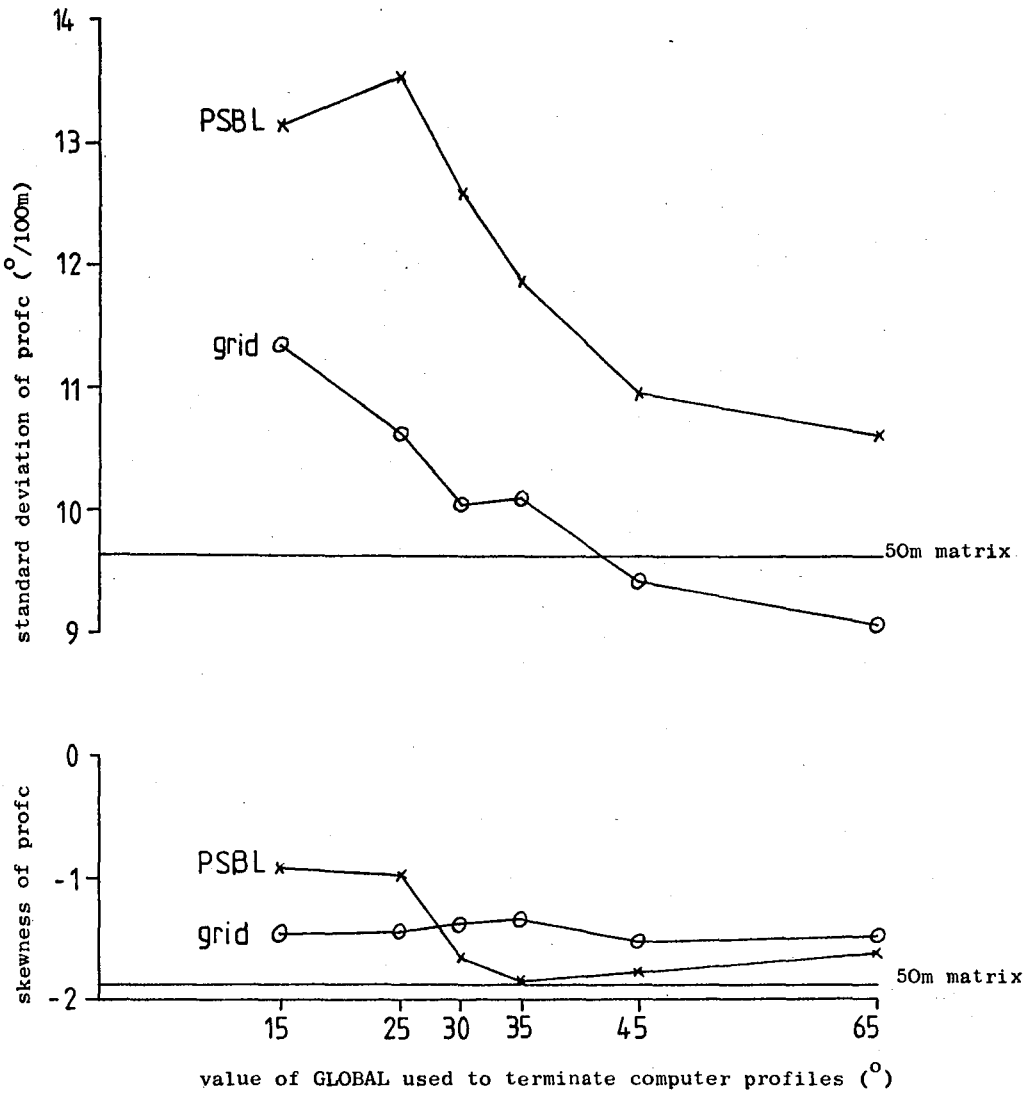


Figure 6.5 : Graph showing variation of standard deviation and skewness of profile curvature for field profiles generated on computer with different values of GLOBAL.

A) gradient from G (degrees) : gradient of inclined line (~5 m long) from SLOPROFIL.2 (degrees) :

9	3 ·	
2	4 ·	679
985	5 ·	02345555679
4	6 ·	244577
0	7 ·	002233

B) profile curvature from G (°/100 m) profile curvature from SLOPROFIL.2 (using Young formula 1 - see section 5.3)

	-5 ·	24
	-4 ·	159
	-3 ·	012
51	-2 ·	04789
7	-1 ·	016
6	-0 ·	559
8	0	
75	1 ·	0
	2 ·	9
	3 ·	0
	4 .	23

Figure 6.6 : Stem-and-leaf plots comparing (A) gradients and (B) profile curvatures generated by SLOPROFIL.2 tracing across two JNJ-fitted squares with those generated by G for the vertices at the corners of the two squares.

(The squares lie on either side of the point of origin of profile 1, Gara catchment).

diagonally across the two squares mentioned above (gradient in this case being obtained as the inclination of a line of 5m horizontal length, and profile curvature calculated by Young formula 1). The upper plot shows that gradients from SLOPROFIL.2 approximately reproduce those from G for the corners of the squares, in spread and in central tendency. Plot (B) shows by contrast that profile curvature values derived from SLOPROFIL.2 are dispersed on either side of the matrix-G values : there is curvature within the two squares that G, sampling at their corners, is not catching. The situation should be evened out to some extent by G's sampling a more complete spatial distribution of profile curvatures, and because not all squares in the matrix will be as internally curved as the two used in the example illustrated in figure 6.6, which came from an area of nose slope on either side of the point of origin of profile 1. However, the discrepancy in summary statistics of profile curvature between G and SLOPROFIL.2 suggests that matrix-G at 50 m resolution never captures all the variability obtainable from the same matrix data sampled at 5 m intervals by SLOPROFIL.2. The important issue of sampling resolution is discussed further in chapter 8.

The reason why the computer profiles according to the PSBL scheme provide higher values of profile curvature than the grid scheme is probably that PSBL profiles sample the steeper valleyside areas most thoroughly because all points of origin start there, and this is where profile curvature is greatest (either positive or negative) on a detailed scale (see section 5.3 ii). The two squares used in the example of figure 6.6 were located in this type of area in the catchment.

Skewness of profile curvature is not badly estimated by any of the matrix-based profile samples. The PSBL actually comes nearest

to G's value for GLOBAL = 35° (figure 6.5) but, for GLOBAL ≥15°, the grid scheme skewnesses show greater consistency, which could be the more valuable property, especially taken in conjunction with the findings on standard deviation detailed above.

6.3 iv Altitude

Column 1 of table 6.1 shows that mean altitude for all the matrix-based profile samples and the field samples is slightly or moderately greater than that for matrix-G, implying that the profiles measured in the field and reproduced here on computer were preferentially located in the higher-altitude headwater areas. For GLOBAL values over 30°, grid sample mean altitudes start to fall, probably because of more coverage of talweg areas (see for example profile 9, figure 6.2) which is undesirable for a hillslope sampling method. The steady rise in mean altitude for PSBL samples with increasing GLOBAL shows the dominant effect of increasing coverage of summit areas up to GLOBAL = 35°, above which mean altitude is stable. Standard deviation of altitude does not show a monotonic trend with value of GLOBAL, but is generally well estimated by all samples; GLOBAL = 45° (grid) and 65° (PSBL) come closest to matrix results. The predominantly negative skewness of altitude is actually reversed for grid schemes with GLOBAL = 45° and over, again suggesting coverage of talweg areas; grid scheme GLOBAL = 25° is most similar to matrix-G for this statistic.

Overall, the altitude statistics obtained appear to be sensitive to the exact locations of profiles within the catchment, since altitude increases from mouth to headwater of this catchment as well as increasing up any one slope (see figure 6.7). It is thus possible to cover the types of slope in the catchment satisfactorily (e.g. concave footslope, upslope convexity, low-gradient summit) without reproducing matrix-G's altitude statistics.

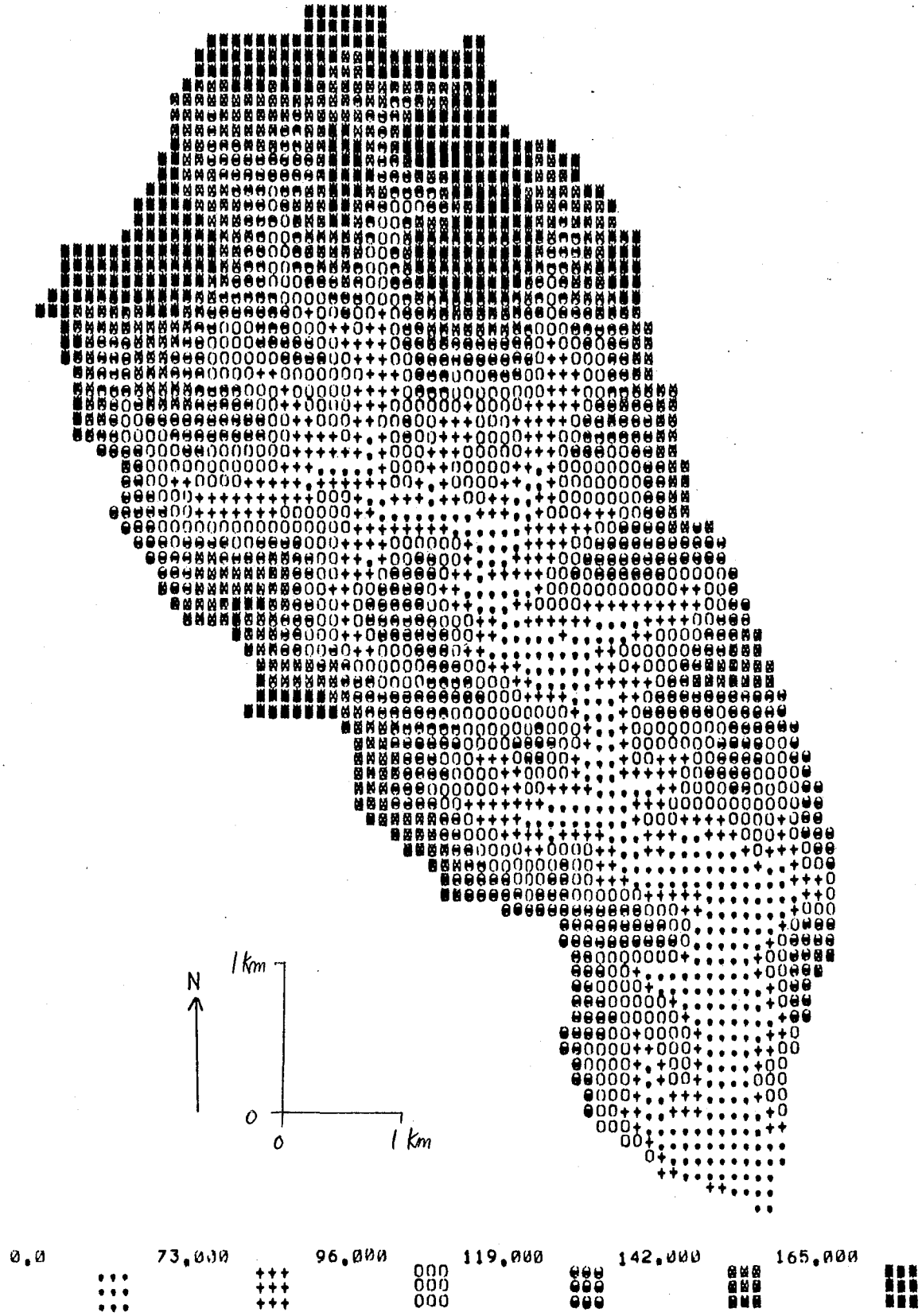


Figure 6.7 : Map of altitude in metres from Gara matrix at 100 m mesh.

It is clearly important to attempt to obtain G's statistics for altitude with matrix-based profiles in the type of situation exemplified by the Gara, as it is an indication that valley mouth and headwater slopes are being sampled, which is desirable. On the other hand altitude statistics are not enough on their own to gauge the completeness of a sample, as is illustrated by the fact that mean altitude for PSBL ORCJ = 10° and GLOBAL = 25° is nearest to matrix-G's although gradient statistics suggest that this computer profile sample is biased towards steeper slopes.

The character of the Gara landscape is well summed up by the altitude/gradient correlation statistics in column 9 of table 6.1 : the relationship is generally strong and negative, showing that the gentler slopes occur predominantly high up in the catchment. For low values of GLOBAL, the matrix-based profile statistic is more negative than matrix-G's because steep slopes nearer the mouth of the catchment and gentler headwater slopes are being sampled, making for a straightforward linear relationship. As the value of GLOBAL is increased, the profiles take in more gentle summit angles, both near the catchment's outlet and further upstream; in the case of the grid scheme in particular some talweg angles are also included, so that the linearity of the relation between altitude and gradient is weakened.

6.3 v Conclusions

This examination of statistics from SLOPROFIL.2 generating profiles from the same points of origin as used in field survey in the Gara catchment, has found that the most satisfactory comparisons with matrix-G statistics are those for gradient. The differences in results between grid and PSBL schemes are interesting however, suggesting that a greater length of PSBL profile (average 365 m for

PSBL GLOBAL = 30°) needs to be measured than is the case for grid (average length 313m for grid GLOBAL = 25°) to achieve satisfactory coverage particularly of low-angled crestal areas. This contrast helps to explain why the grid scheme profile sample measured in the field produced more reliable gradient statistics than the field PSBL, although in both cases the field-measured profile lengths were on average shorter (rightmost column, table 6.1) than the figures quoted above. This was partly because non-morphological obstructions such as crops were encountered in field survey, and partly because of lack of knowledge as to where to terminate a profile in the field in the absence of recommendations in the literature for slopes curved in plan.

The evidence from profile curvature, although complicated by the issue of resolution, seems to favour strongly the grid sample as a method of obtaining a value for the standard deviation of this attribute that is not artificially increased by a large sample of valleyside as opposed to crestal slopes.

The altitude statistics have been interpreted as showing that the sample of profiles surveyed in the field, from 15 PSBL points of origin and 16 grid, was biased towards headwater and therefore higher-altitude slopes. In the next chapter larger computer-generated profile samples will be analysed, to evaluate the generality for the Gara catchment of the results produced here. In the following section the spatial coverage of profiles resulting from use of large numbers of points of origin located according to various sampling schemes is investigated. Conclusions from these visual evaluations will aid the interpretation of statistical results in the following chapter.

6.4 Spatial coverage of profiles from different sampling schemes

i. Introductory remarks

For the Gara catchment two general categories of profile sampling will be contrasted : namely, the surface-random type involving points located without consideration of topography (e.g. grid scheme); and the surface-specific type, located according to some topographic rules (e.g. profile sampling baseline (PSBL), river and divide schemes). The topography of the Netherhearth catchment is not sufficiently dissected to make a surface-specific scheme viable : it is largely meaningless to draw divides between numerous and often parallel-flowing channels, which rules out a PSBL scheme. Since many of the channels follow the catchment's slope with no flanking valleysides of their own, profiles drawn from talweg points of origin would follow the course of the Sike, which is not the usual aim in slope studies. The two surface-random methods of locating points of origin - grid and random spacing - will be investigated for that catchment in chapter 7.

The fact that surface-specific schemes cannot be applied in the Netherhearth catchment immediately suggests a drawback to them : they are not applicable in all topographies. However Young's profile sampling baseline has been used by other geomorphologists, notably Abrahams and Parsons (1977) and Parsons (1979, 1982). The Gara represents the sort of catchment more studied by slope profilers, so various starting-point options are explored below for this catchment.

It would be time-consuming on computer to generate profiles over the whole of the Gara catchment with the high density of surface coverage to be explored below. Therefore the majority of the schemes were tested only on the south-western part of that catchment, including the valley of Slapton Wood Stream and several valleys north of it.

This part of the catchment was judged to incorporate some interesting topographic contrasts - some straight valleyside, some curved valley head areas, and areas of nose slope at tributary junctions - which would provide adequate testing of the ability of the various schemes to cover the sort of topography found over the Gara catchment with profiles.

6.4.ii Profile sampling baseline scheme

Figure 6.8 shows the south-western portion of the Gara catchment with matrix-based profiles starting from every point that was digitized along the PSBL as described in chapter 2. Terminating conditions have been allowed to be very generous (ORCJ = 20°, GLOBAL = 65°; note that in section 6.3 it was found that ORCJ = 10° and GLOBAL = 30° gave gradient statistics most like G's for matrix-based profiles located by PSBL). This was because the aim was to find out if any areas are altogether unreachable from PSBL points of origin.

It is clear from figure 6.8 that summit areas are not getting much coverage by PSBL scheme profiles. Coverage is fine for slopes relatively straight in plan, as along the southern side of Slapton Wood marked with a '1' on figure 6.8; however upslope concavities (e.g. at '2') and downslope convexities (at '3') repel profiles, which concentrate on upslope convexities and downslope concavities. This was the argument used by Young (quoted in chapter 2) against surface-random sampling, yet it is not avoided here by an implementation of the surface-specific scheme recommended as an alternative.

The PSBL in figure 6.8 was constructed by taking contour configuration into account in deciding how large a loop to allow the PSBL to describe around a first-order stream and into an area of nose slope at the junction of two streams. This modification was judged to be necessary to avoid oversampling of short first-order valley

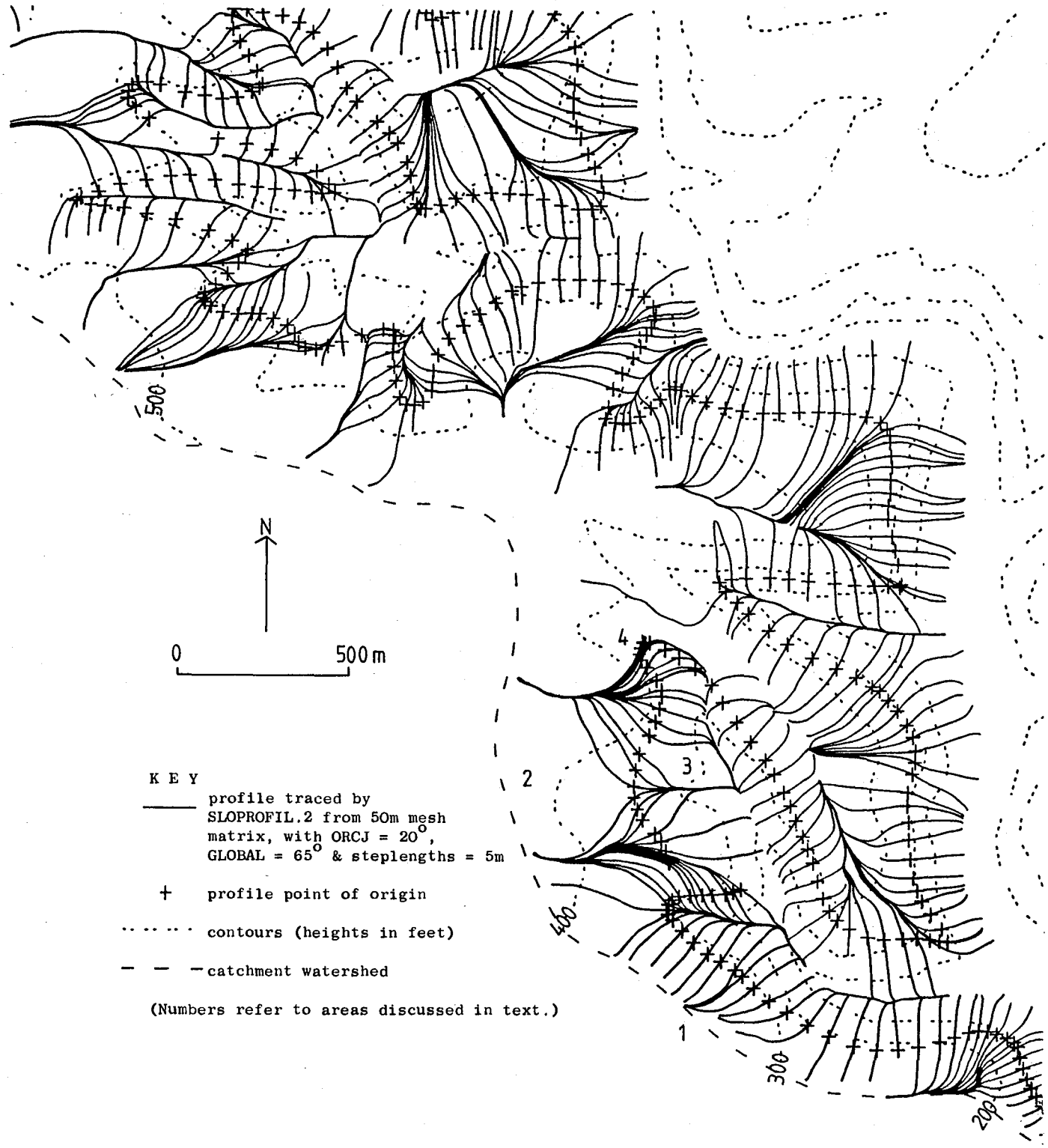
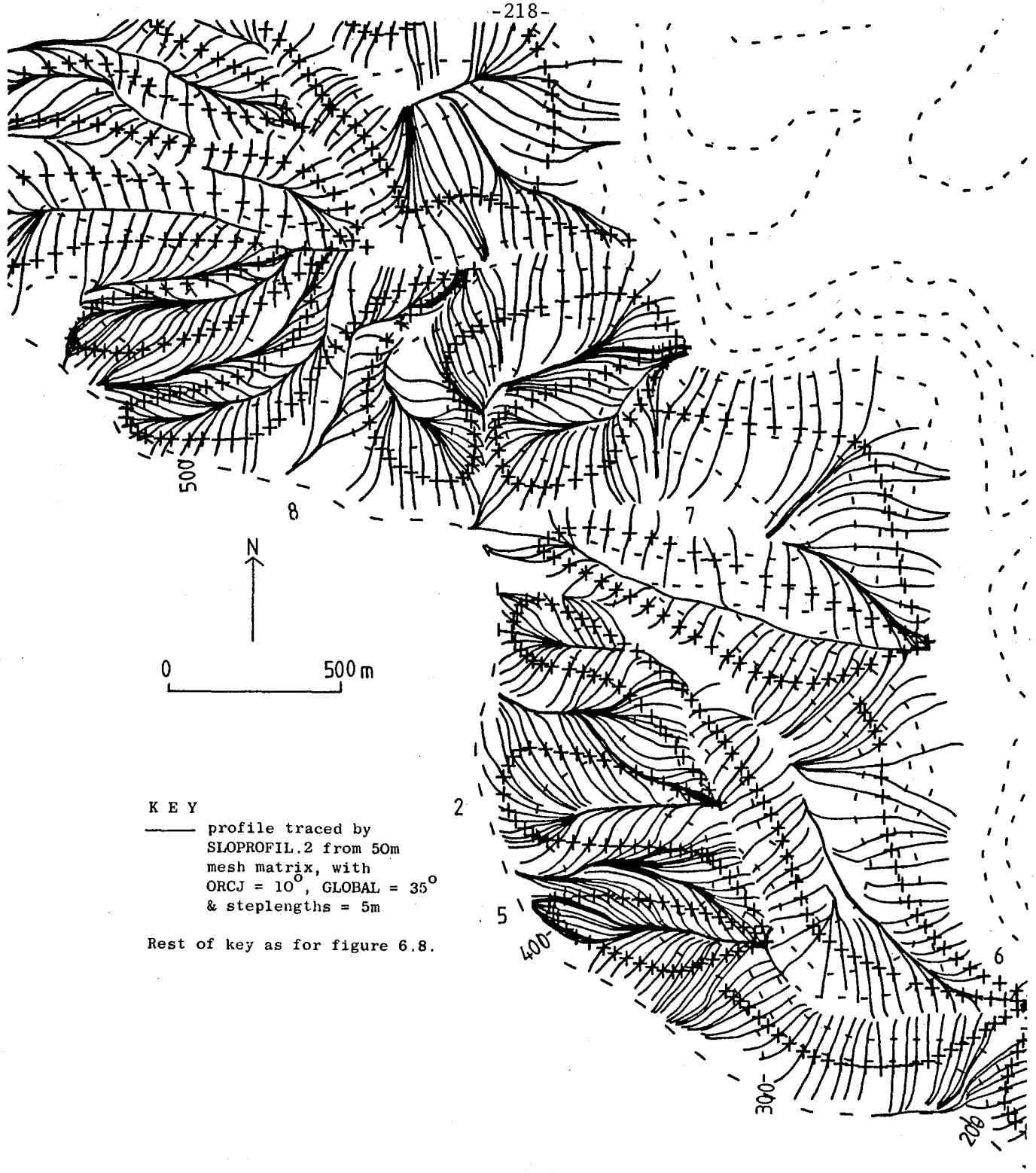


Figure 6.8 : Profiles in the south-west of the Gara, generated from digitized points along the first PSBL.

slopes, as was explained in chapter 2 (figures 2.5 and 2.6). It could be argued however that the restricted PSBL constructed for this study is unfair to the scheme when it comes to judging the spatial coverage of profiles generated from it.

Therefore a second PSBL was constructed, to pass in all places exactly half-way between divides and talwegs. This time talwegs were defined to extend as far up a tributary valley as was indicated by the existence of kinks (referred to as crenulations in the literature - e.g. Gardiner, 1975, 11) in the contours, rather than being restricted to the topographic lows marked with a blue line on the 1:25,000 maps as previously. This PSBL was also digitized, and profiles generated from every digitized point along it to produce figure 6.9.

It is clear from a comparison of figures 6.8 and 6.9 that the PSBL constructed strictly half-way between divides and talwegs, as defined by contour crenulations, produces the more complete spatial coverage of profiles. A good example of the improvement is illustrated at the location marked with a '2' on figures 6.8 and 6.9 : this is a valleyside hollow which contained no blue line indicating a stream on the 1:25,000 map but which was defined as a talweg by the presence of a series of contour crenulations consistent with a linear depression in the land surface. The second PSBL therefore describes a large loop around this area, while the PSBL of figure 6.8 makes only a small deviation here to parallel the contours. By taking the PSBL up near to the divide in this area, the profiles are bound to cover the upslope concavity shunned by profiles in figure 6.8. Success in areal coverage by PSBL scheme profiles is thus demonstrated to be very dependent on the initial construction of the PSBL. The results of this investigation show that if the sole criterion in a study is to achieve as complete a coverage of the area by profiles as possible,



KEY

——— profile traced by SLOPROFIL.2 from 50m mesh matrix, with ORCJ = 10°, GLOBAL = 35° & steplengths = 5m

Rest of key as for figure 6.8.

Figure 6.9 : Profiles in the south-west of the Gara, generated from digitized points along a PSBL taken half way between divides and contour crenulations.

a PSBL taken half-way between divides and talwegs defined by contour crenulations, penetrating well upslope into stream source areas, is essential.

The coverage of the area by profiles as shown in figure 6.9 is not even, however. Small first-order valleys are heavily sampled here, as for instance in the valley east of the '5' marked on figure 6.9. There is also a problem of a high density of profiles on divides around first-order tributaries when the PSBL is taken right down to the confluences of streams as is the case in figure 6.9. This oversampling comes about when the divide is plunging, and all the profiles can follow it without swinging through a large bearing. There is definitely a case in this situation for taking more notice of contours rather than drawing the PSBL at all times half-way between divide and talweg as Young suggests. One should only extend a PSBL right down to a tributary junction if the contours come to a sharp point there, as at '6' on figure 6.9.

Some summit areas on figure 6.9 are not reached by profiles that invariably start below them and may need to turn through a large angle to reach them, as at '7' and '8' on figure 6.9. Terminating conditions for the profiles reproduced in figure 6.9 were set at values (ORCJ = 10°, GLOBAL = 35°) like those found to give summary statistics similar to G's, and more restricted than the conditions used for figure 6.8. This was because figure 6.9 was designed to demonstrate the density of coverage of the area achieved by the more complete PSBL scheme, whereas the run that produced figure 6.8 was conceived to show where slope orthogonals could end up if constrained to start in locations low down in the topography.

To summarize, figure 6.9 shows that a PSBL defined half-way between divides and contour-crenulated talwegs leads to an oversampling

of first-order valleys (to verify this, look at the figure with eyes half-closed and compare density of black lines on the lower left-hand side with that on the lower right). The alternative PSBL as conceived in chapter 2 and implemented in the field survey in the Gara, is shown by figure 6.8 to exclude substantial areas of summit from sampling altogether. This is a choice that geomorphologists embarking on survey should be aware of if they choose the PSBL to locate their points of origin. It would be advisable to generate a large sample of profiles from a newly-constructed PSBL using SLOPROFIL.2 in the manner of figures 6.8 and 6.9 before any field survey was undertaken. Lack of coverage in any area would then be made clear and steps could be taken (e.g. by altering the PSBL) to allow profiles to reach it. This precaution can, however, make substantial demands on computing resources (see section 4.5 where computer time used by SLOPROFIL.2 is quoted).

6.4.iii Grid sampling scheme

Figure 6.10 shows a set of profiles generated by taking every altitude matrix vertex as a point of origin and using the same terminating conditions (ORCJ = 10°, GLOBAL = 35°) as were used for the large sample of PSBL profiles in figure 6.9. It is apparent that coverage of the surface by grid profiles is more complete than from either implementation of the PSBL scheme discussed in the previous sub-section. With a grid scheme, some degree of coverage is found throughout the entire area because coverage of the surface by points of origin is complete. This finding is necessary but not sufficient to recommend it for use.

The other necessary finding is that most of the grid points of origin can form the starting locations for a realistic profile : there

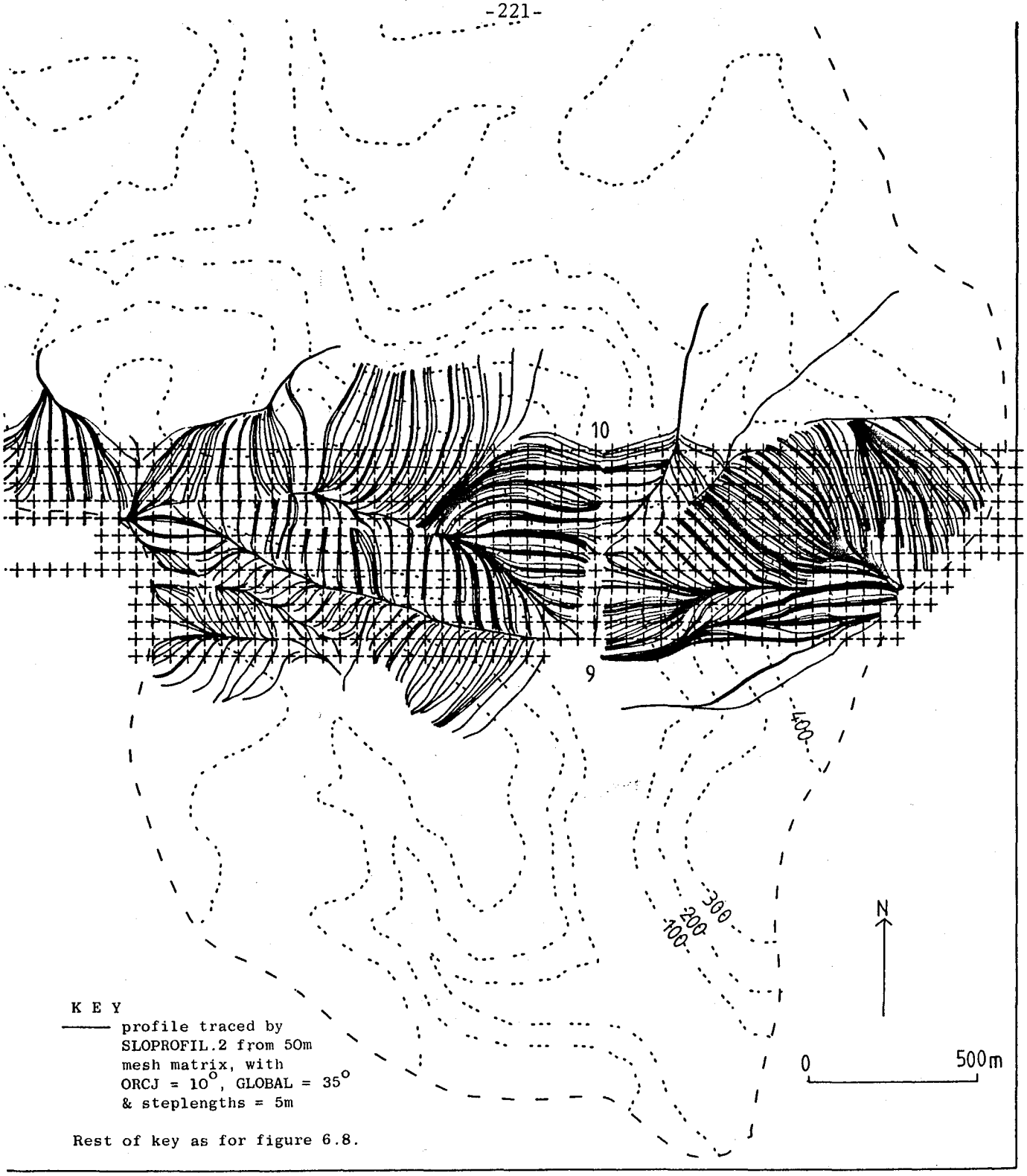


Figure 6.10 : Profiles generated from every vertex of the 50 m mesh Gara matrix over an area in the southern part of the catchment.

is no evidence on figure 6.10 to suggest that profiles starting on a summit, for example, tend to continue for a short while and then stop. The main exception to this statement is a desirable one : that some points of origin on the main stream flood plain area between the locations marked '9' and '10' on figure 6.10 terminate very quickly. Such areas are not usually included in slope studies.

It would seem to be the case from looking at figures 6.8, 6.9 and 6.10 that it is easier (requires smaller changes in bearing) to trace a profile downslope from a point of origin on a summit area, than it is to trace one upslope into a summit area from a point of origin on the valleyside lower down (as for PSBL profiles). This accords with the finding in the field when surveying a profile up a slope, that when the crestal area was reached it would often appear to be sloping at approximately 90° to the profile path and so the latter would be terminated. For this reason grid profiles, some of which start on summit locations, lead to greater coverage of summit slopes than can easily be achieved from the PSBL. Another encouraging finding for the grid scheme is that profiles terminate at the talwegs in the vast majority of cases, which avoids over-sampling of those areas on which all profiles would converge. There is a discernible tendency for profiles to converge on downslope hollows and upslope spurs, but even spacing of points of origin guarantees that <u>some</u> profiles go through all types of area.

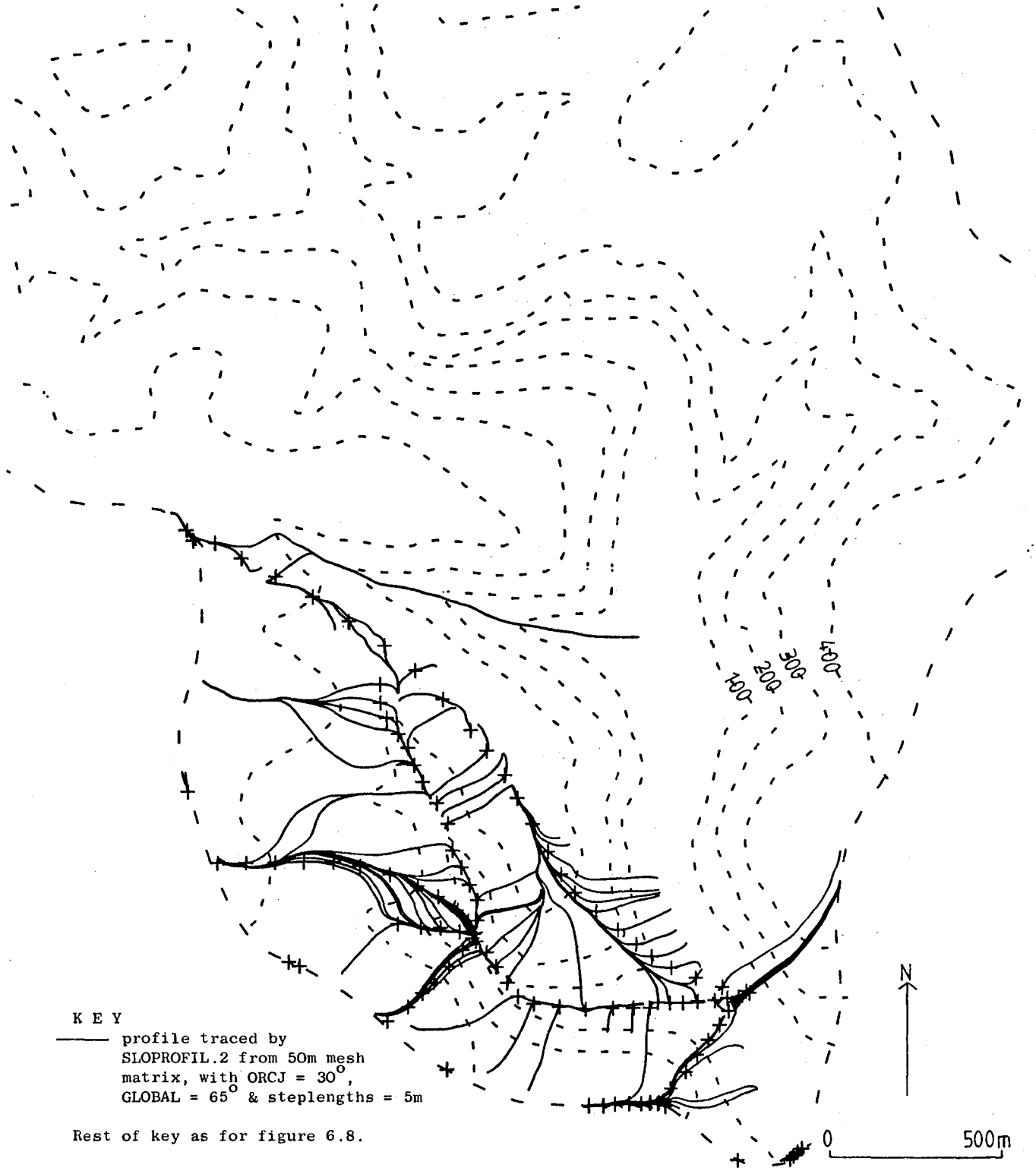
It must be the case however that long slopes are over-sampled by grid scheme profiles, compared with shorter slopes. This is because even areal coverage is already achieved by the spacing of points of origin, so that the generation of longer profiles on a long slope will cause that slope to receive denser coverage of profiles. This can be seen in figure 6.10, where the long slope on the east side of

the main valley is more thickly covered with profiles than the divide flanked by talwegs on the west side. This bias can be countered by giving profiles equal weight in analysis regardless of length, as will be described in the next chapter. By contrast no statistical method can eradicate the effect of denser coverage by PSBL profiles of first-order valley slopes as was shown in figure 6.9. The grid scheme is also totally free from dependence on any difficult subjective decisions, made prior to profiling, on the location of streams and divides.

6.4.iv Stream and divide scheme

A suggestion made earlier in this thesis, when discussing the problems of undersampling of downslope noses and upslope concavities, was to commence profiles at stream and divide points of origin, each maximizing one type of bias while minimizing the other, and so possibly cancelling out bias overall. Figure 6.11 shows that the initial attempt to use SLOPROFIL.2 in this way was unsuccessful, because the fact that divides in the Gara are often plunging, means that profiles with a point of origin on a divide will tend to follow it for some distance before eventually descending a slope, and so crestal areas will be oversampled. Talweg points of origin incorporate the danger that profiles will follow the talweg for some way, and their location causes them grossly to undersample upslope concavities.

Figure 6.12 represents an attempt to improve this situation while still using stream and divide points of origin. The algorithm to do this is included as an option in SLOPROFIL.2. The aim is to commence each profile some way from the actual talweg or divide, so that the tendency of profiles to follow these two form lines is minimized. The input to the program still consists of digitized stream and divide points, but on selection of the stream and divide



K E Y

——— profile traced by SLOPROFIL.2 from 50m mesh matrix, with ORCJ = 30°, GLOBAL = 65° & steplengths = 5m

Rest of key as for figure 6.8.

Figure 6.11 : Profiles generated from digitized points along Slapton Wood Stream and its confining divides.

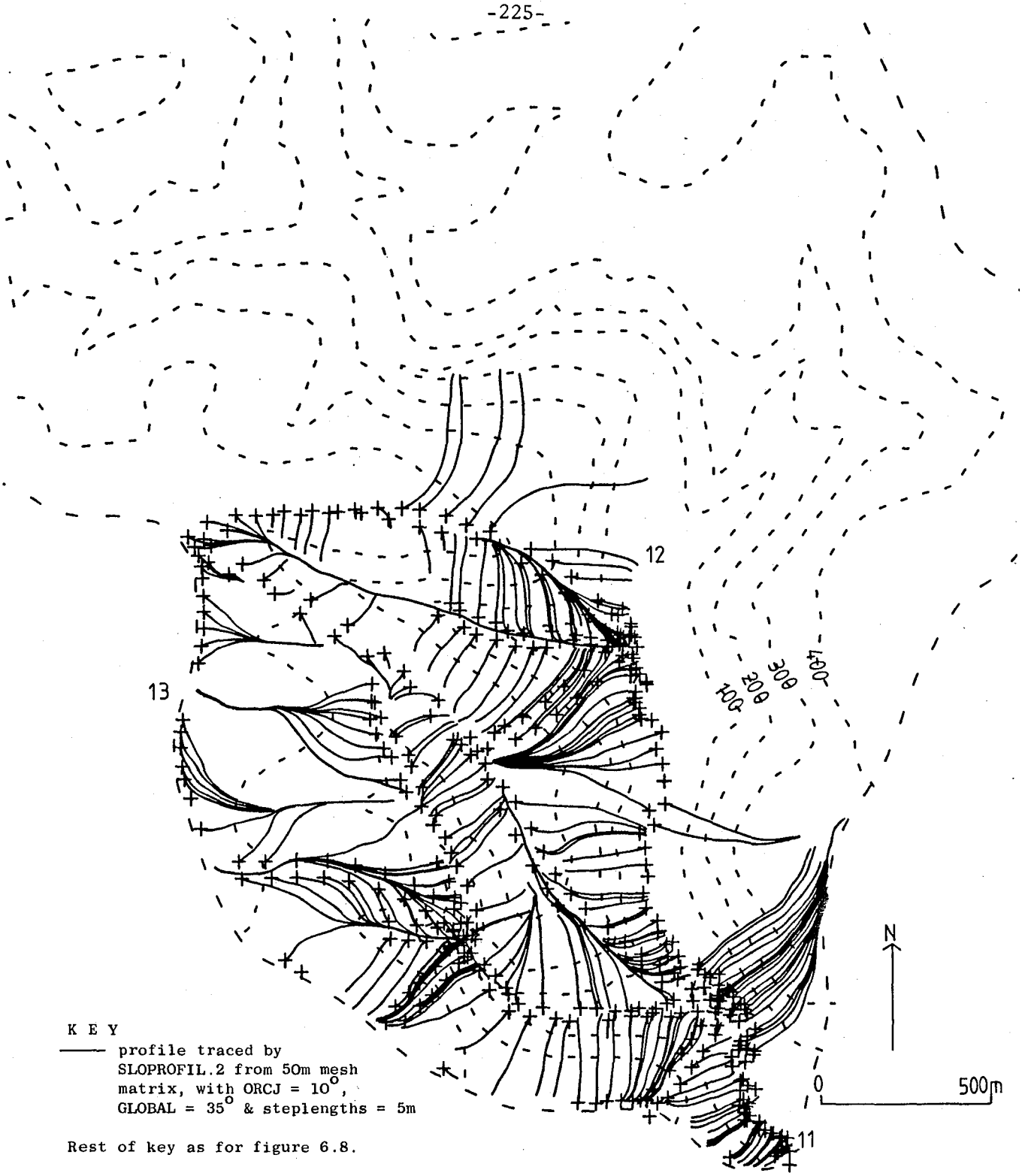


Figure 6.12 : Paired profiles commencing 25 m on either side of points along Slapton Wood Stream and its confining divides.

option (IFSND = 1), SLOPROFIL.2 first determines the orientation of the first step to be taken from the starting-point. The assumption is that this direction represents the bearing of the plunge of the talweg or divide. It then defines two points of origin AMULT (value chosen by user) steplengths away from the input point of origin and at 90° to the direction of plunge already determined. For a talweg, these two points represent the downslope ends of two profiles that should then be traced upslope, one on each side of the talweg, until termination in the usual way; no downslope trace is implemented. For a divide, the converse is true.

For figure 6.12 AMULT was set to such a value that profiles started 25 m on either side of stream and divide. It is clear from a comparison of figures 6.11 and 6.12 that the modification represents an improvement in stopping profiles from following stream and divide. Looking closer it is clear that some paired profiles descend/ascend on the same side of a divide/talweg instead of the opposite sides as intended. This is inevitable if the definition of streams and divides input as starting-points does not quite agree with the location indicated by the matrix altitudes. This is a particular problem for the gentle summit areas of the Gara, but is also manifested in the talweg profiles generated on either side of the main stream (defined as the location of the blue line on the 1:25,000 map) between '11' and '12' on figure 6.12,which mostly proceed in a westerly direction. For a similar reason, the PSBL profiles on figure 6.8 in the area marked ' 4' all ascend to the west rather than describing a horseshoe pattern around the source of Slapton Wood Stream, because the position of the talweg as defined by the blue line in that place did not agree with the position indicated by the matrix data, and the PSBL had been constructed to pass near to the blue line to avoid oversampling of first-order valleys

(as was described in chapter 2). In chapter 9 on the Ferro catchment talweg and divide are defined from the matrix, rather than independently.

The two types of bias due to plan curvature (convergence of profiles on upslope convexities and downslope concavities) are alternately maximized and minimized in figure 6.12, but the areal coverage of profiles achieved by this scheme is not even, as can be seen clearly at the location marked '13' on the figure. A slope with appreciable plan curvature will be very unevenly sampled away from the stream and divide. In the following chapter investigation will be carried out to see if this bias is important statistically.

6.5 Conclusions

In the first major section of this chapter, various terminating conditions were tried out on matrix-based profiles located similarly to the field profiles surveyed in the Gara. This formed an introduction to the issues involved in the fixing of terminating conditions, to be performed on larger profile samples from both the Gara and the Netherhearth catchments in the next chapter. The comparisons made between statistics from these profiles and from the matrix analysed by program G indicated that grid profiles with GLOBAL$\approx 25°$ and PSBL profiles with GLOBAL$\approx 30°$ gave most balanced coverage of the surface. Similar terminating conditions were then used to generate large samples of profiles to investigate the success of various profile sampling schemes in terms of spatial coverage of profiles produced, in the second major section of this chapter.

Some experimentation was needed in section 6.4 to determine the best PSBL and stream and divide schemes to yield even spatial coverage of profiles. The results are shown to be deficient in some respects in the relevant sections, but geomorphologists who wish to

implement such schemes can learn from the findings set out here, and use the options in SLOPROFIL.2 designed to achieve the best coverage. The grid scheme is the easiest to implement, but is not immune from uneven coverage. All this tends to confirm Evans' suggestion that 'it is inherently impossible to produce a set of surface-specific lines (slope lines) which is an unbiassed representation of an irregular surface' (1979, 18). However some of the bias in the grid scheme can be counteracted by weighting in analysis, to be described in the next chapter.

The grid scheme has not as yet found general favour with profilers. Hack and Goodlett (1960) did trace profiles up- and downslope from a grid pattern of points to determine the maximum gradient on a slope together with its aspect. Grid sampling has also been recommended for use in computing the mean distance of travel of the water within a drainage basin (Busby and Benson, 1960) and to determine overland flow distance and slope needed by the Stanford Watershed Model (Fleming, 1975). The former study found that use of between 20 and 35 grid intersections per drainage basin yielded accurate results. There are also a number of studies that have used a grid intersection method to estimate drainage density, as a less tedious alternative to the measurement of stream lengths (cited in a review paper by Gardiner and Park, 1978). Bunting (1964) investigated soil depth by augering samples on a grid pattern. In all these studies the target for study was recognized to be areally-based, and a systematic sample seen as the most efficient way of estimating that target. In slope studies,the target for sampling is seldom seen as an area, and more often as a subset of an area (e.g. all slopes relatively straight in plan) which is defined subjectively. There is a case however for viewing slope profiling as an areal study, since the majority of the land surface is a slope of some degree.

The problem with the PSBL boils down to the problem of numerically defining what a slope is. This is because in order to allow all slopes to be surveyable from it, the PSBL must be constructed to pass through all slopes. But when (for example) a divide plunges down to a nose separating two streams near their junction, its component slopes become diminishingly small. Where is the legitimate cut-off point? The answer cannot be set down for all time : it depends on the topography and on the purpose of survey.

The stream and divide option could represent a pragmatic choice in the field where it may be difficult to identify a PSBL. A problem is again encountered prior to survey, in defining these two types of form line. The most satisfactory solution could be to contour from the matrix and draw in talwegs and divides on such a contour plot. These would be more likely to agree with SLOPROFIL.2's estimation of where these two form lines were than did the talweg and divide used in section 6.4.iv.(The latter were digitized off the original map of the Gara). This option of defining talweg and divide from the matrix is pursued in the analysis of the Ferro catchment in chapter 9.

Although the spatial coverage of stream and divide profiles does not look encouraging here, the importance of such bias statistically will be investigated in the next chapter. The same will also be done for grid and PSBL schemes.

CHAPTER 7 : ESTABLISHMENT OF OPTIMUM COMPUTER PROFILE SETS IN THE GARA AND NETHERHEARTH CATCHMENTS

7.1 Introduction

7.2 Determination of profile sampling design for Gara catchment

i. Grid scheme

ii. Profile sampling baseline scheme

iii. Stream and divide profiles

iv. Conclusions on a Gara profiling scheme

7.3 Matrix-based profiles in the Netherhearth catchment

7.4 Implications of restriction to 'slopes relatively straight in plan'

7.5 Some comments on appropriate density of profile sampling

7.6 Conclusions

7.1 Introduction

The demonstration of the spatial coverage achieved by various profile sampling schemes in the previous chapter should help the geomorphologist to decide on the pattern of profiles to use before embarking on field survey. It is interesting however to see how the biases shown in section 6.4 are reproduced in profile statistics from the various sampling schemes.

In section 6.3 terminating conditions were fixed for the sample of profiles measured in the field in the Gara catchment. This introduced the issues involved in calibrating the lengths of matrix-based profiles to provide even spatial coverage. It is recognized that the Gara field survey may not have included enough profiles, and that omissions of whole profiles in the field may have produced a biased coverage, so in section 7.2 the results of generating larger profile surveys on computer are presented for the Gara. Appropriate lengths of profile output from SLOPROFIL.2 are found by experimenting with different values of ORCJ and GLOBAL (the variables bringing about termination of profiles in the program due respectively to large local orientation change, and to large difference from the orientation of the rest of the profile : figure 6.1) while using comfortably large profile sample sizes, and then reducing the latter until the smallest number of computer profiles to give statistics consistent with those from the larger samples is found. In section 7.3 this procedure is repeated for the Netherhearth catchment.

Much has been said in this thesis about the common restriction of profiling to measurement of 'slopes relatively straight in plan' (Young, 1974, 14). In section 7.4 the implications of this restriction for summary statistics of land form attributes obtained are investigated.

This will permit conclusions about the effect of this restriction on data from areas with some slopes curved in plan.

7.2 Determination of profile sampling design for Gara catchment

i. Grid scheme

Table 7.1 rows 1 to 3 display summary statistics from various samples of matrix-based profiles for the Gara catchment according to a grid design of starting-point locations. Results from three large profile samples are presented, to determine terminating conditions for a comfortably large profile sample before investigating the stability of summary statistics obtained as this sample size is decreased.

Although it was found in section 6.3 that, for a 16-profile design like that measured in the field, grid scheme profiles with GLOBAL=25° gave statistics most similar to those from the matrix analysed with G, for a large sample of matrix-based profiles (row 1 table 7.1) this value of GLOBAL gave too high a figure for mean and for standard deviation of gradient. Of the large profile samples with GLOBAL = 30° and 35° (rows 2 and 3), neither reproduces matrix-G gradients entirely satisfactorily : the GLOBAL = 30° scheme produces a good estimate of mean gradient but overestimates its standard deviation; the GLOBAL = 35° scheme is more acceptable for the latter although it underestimates mean gradient.

Rows 1,2 and 3 of table 7.1 show that as GLOBAL is allowed to increase from 25° to 35°, mean gradient for the large samples of matrix-based profiles decreases from 7.63° to 7.26°, whereas that for the 16-profile sample (table 6.1) decreased more substantially from 7.77° to 6.84°. A suggested reason for this contrast is that greater coverage of the surface by profiles in the large sample lessens

Table 7.1 : Summary statistics for matrix-based profile samples replicating various properties of matrix-G statistics, Gara catchment

Design (value of GLOBAL in brackets)	No. of profiles	Altitude (m)			Gradient (°)			Profile curvature (°/100m)		Average profile length (measured horizontally) (m)
		mean	st.dev.	skew	mean	st.dev.	skew	st.dev.	skew	
1) grid (25°)	134	128.20	40.27	-0.31	7.63	4.72	1.33	10.90	-1.63	330.97
2) grid (30°)	134	128.41	40.53	-0.31	7.45	4.70	1.36	10.62	-1.62	380.34
3) grid (35°)	134	128.34	40.22	-0.30	7.26	4.66	1.38	10.45	-1.63	413.06
4) PSBL (30°)	137	120.88	38.59	-0.13	8.05	5.16	1.46	12.46	-1.54	347.88
5) PSBL (40°)	137	122.17	39.43	-0.06	7.41	4.98	1.57	11.66	-1.59	425.66
6) PSBL (40°)	39	120.77	37.73	-0.39	7.49	5.05	1.51	12.44	-1.43	424.23
7) PSBL (40°)	20	133.33	40.81	-0.05	6.96	4.84	1.40	11.20	-1.63	444.50
8) PSBL (40°)	10	129.71	38.48	-0.10	7.21	4.48	0.86	12.16	-1.94	378.50
9) divide (40°)	122	114.64	36.08	-0.47	7.44	4.53	1.70	12.24	-2.03	235.33
10) divide (40°)	38	122.79	35.23	0.10	7.43	4.35	1.20	10.28	-1.11	227.00
11) divide (40°)	19	123.30	36.17	0.16	8.63	5.01	0.93	11.98	-0.94	233.68
12) divide single (40°)	19	121.37	36.95	-0.07	8.14	4.65	1.32	10.91	-0.67	203.16
13) stream (25°)	37	118.09	29.99	-0.60	7.80	4.96	1.36	9.98	-0.73	306.22
14) stream (30°)	37	126.79	34.89	-0.12	7.06	4.67	1.53	8.99	-0.74	402.84
15) 50m mesh matrix		120.59	39.60	-0.40	7.40	4.55	1.16	9.62	-1.87	

Note 1 : steplengths used for all matrix-based profiles were 5 m (measured horizontally)
Note 2 : statistic is underlined if matrix-G value + 2% ≥ profile value ≥ matrix-G value - 2%

the importance of terminating conditions in ensuring complete coverage of the land surface types. This finding suggests that for the sort of small profile sample sizes measurable in field surveys more importance must be attached to determination of correct terminating conditions than is necessary when sampling large numbers of profiles. However since an aim of this research is to demonstrate how to generate on computer a set of profiles appropriate for field survey, it is reasonable to be concerned here with the effects of terminating conditions in small samples.

A serious charge against the grid profile scheme is its persistent over-estimation of mean altitude, seen in rows 1, 2 and 3 (matrix-G figure is 120.62m). The reason for this must be that longer slopes in the high-altitude headwater areas of the catchment (such as the slope leading towards the triangulation pillar, sampled in the field by profiles J and 19) are being oversampled. This is because the (even) spacing of points of origin already guarantees representation to a longer slope commensurate with the greater area it covers, and the greater length of profiles on long slopes in addition to this will therefore lead to their being more thickly covered with profiles than short slopes, as was shown in section 6.4.iii. It was suggested there that this effect could be counteracted in analysis by weighting the individual measurements such that each profile is assigned a weight equal to one, instead of each steplength receiving a weight of one as in table 7.1. If each profile is to get a weight of one, each of its component steplengths must be weighted by the reciprocal of the number of steplengths in that profile. Results of this type of analysis are presented in table 7.2.

The first three rows of table 7.2 show results from large matrix-based profile samples, with weighting applied. It is clear

Table 7.2 : Summary statistics of land form properties from profiles generated by SLOPROFIL.2, giving each profile weight equal to 1

Design (value of GLOBAL in brackets)	No. of profiles	Altitude (m)			Gradient (°)			Profile curvature (°/100m)		Average profile length (measured horizontally) (m)
		mean	St.dev.	skew	mean	st.dev.	skew	st.dev.	skew	
1) grid (30°)	134	122.22	38.94	-0.38	7.84	4.95	1.22	12.35	-1.32	380.3
2) grid (35°)	134	122.82	38.82	-0.40	7.66	4.94	1.26	12.18	-1.33	413.1
3) grid (40°)	131	123.87	38.81	-0.41	7.51	4.89	1.30	11.98	-1.40	450.8
4) grid (30°)	37	120.88	41.50	-0.17	7.88	5.23	1.12	12.64	-1.31	391.6
5) grid (30°)	20	122.67	40.47	-0.36	7.81	5.33	1.32	11.98	-1.31	417.8
6) grid (35°)	20	120.81	38.96	-0.39	7.60	5.29	1.36	11.91	-1.30	433.5
7) grid (40°)	20	122.19	38.96	-0.46	7.43	5.30	1.37	11.68	-1.30	499.3
8) grid (45°)	20	123.45	39.68	-0.26	7.18	5.10	1.31	11.33	-1.24	580.5
9) psbl (40°)	20	121.05	37.20	0.15	8.09	5.49	1.20	13.59	-1.01	444.5
10) psbl (55°)	20	123.74	37.89	0.13	7.52	5.64	1.26	13.77	-0.64	531.8

See notes 1 and 2, table 7.1.

that the estimates of mean altitude are brought much nearer to matrix-G's by the modification. Standard deviation of altitude continues to be well estimated by the profile samples. Skewness of altitude is also in good agreement with G's. However the modification has also changed the summary statistics for gradient and profile curvature. G's mean gradient is now best estimated by the profile sample with GLOBAL = 40°, but standard deviations of gradient and profile curvature are overestimated to a greater extent than in table 7.1.

Longer profiles in the Gara tend to be more monotonous in the sense of having less variable gradient and profile curvature, and allowing these profiles to carry less weight in analysis has caused the two standard deviations to reflect more the situation on shorter slopes nearer to the catchment's outlet. However it was shown in section 6.3 that profile curvature as estimated by results from SLOPROFIL.2 tracing across two squares of the altitude matrix had a wider dispersion than that of G values calculated at the corners of the same squares : some disagreement between results from matrix-based profiles and G for this statistic seems inevitable. The reasons for this will be explored much more thoroughly in the investigations into scale effects in the next chapter. The disagreement between G and matrix-based profiles for standard deviation of gradient is much smaller than the discrepancies in profile curvature, again confirming the finding reported in section 6.3.

Rows 4 to 8 inclusive of table 7.2 present results from smaller samples of grid profiles (analysed again with weighting), to give an indication of sensitivity of results to sample size. The results are encouraging for a fieldworker wanting to keep the number of profiles for survey to a minimum : for example the 37-profile sample (row 4) produces results no nearer to the 134-profile sample (row 1) than does the sample of 20 profiles (row 5).

The 20-profile samples with various values of GLOBAL (rows 5 to 8) all agree well with all matrix-G altitude statistics. This suggests that altitude is insensitive to the different degrees of coverage of the surface provided by different terminating conditions. The evidence suggests that correct altitude statistics follow if profiles are located evenly over the catchment's incline (from south to north in the Gara) and if no profile on any part of this incline receives more weight than another profile. Thus good reproduction of matrix-G's altitude statistics is necessary but not sufficient to demonstrate that a profile sample covers all land surface types in an area. The 20-profile samples are also consistent with the large profile samples in table 7.2 in representing matrix-G's mean gradient best with GLOBAL = 40°.

To summarize, the altitude statistics have shown that weighting is important for grid profiles to ensure that they do not over-represent long slopes. Mean gradient, which varies with the value of GLOBAL (and hence profile length) chosen, can also be made to agree with matrix-G's statistic, for a value of GLOBAL = 40°. Standard deviation of gradient and profile curvature also decline with increasing GLOBAL, but estimates from profiles are greater than matrix-G's, making their use for fixing terminating conditions problematic : more will be said on this in the next chapter. One of the most encouraging findings is the stability of the statistics over a decrease in profile sample size : a well-located field survey of twenty profiles would not be inadequate to characterize the land surface on the evidence presented here.

7.2.ii Profile sampling baseline scheme

Summary statistics from large matrix-based profile samples, with points of origin along the baseline as defined in chapter 2, are presented in table 7.1 rows 4 and 5. GLOBAL = 40° gives a figure

for mean gradient most like matrix-G's (row 15 table 7.1), while altitude statistics agree well with G's for both samples, by contrast with unweighted grid profiles (also displayed in table 7.1). PSBL profiles overestimate standard deviation of gradient and profile curvature by a considerably greater amount than do grid-profiles-without-weighting, but are more similar to grid-profiles-with-weighting (displayed in table 7.2).

There is stability in summary statistics over a drop in profile sample size from 137 (row 5) to 39 (row 6), but for the 20-profile sample (row 7) both mean altitude and mean gradient have fallen out of agreement with G for the same GLOBAL as previously. Mean gradient is closer to G's for a 10-profile sample (row 8) in fact. All this suggests that a larger sample of PSBL profiles needs to be measured to ensure an even coverage of the surface than with grid profiles, for which a sample size of 20 was judged sufficient in the previous sub-section.

For purposes of comparison with the grid scheme, PSBL scheme profiles were subjected to the same sort of weighting procedure described in the previous sub-section and the results are displayed in table 7.2 rows 9 and 10. The weighting is shown to have no merit in this case : agreement with G's altitude is preserved, but it was good in the first place. Mean gradient does not come into line until a value for GLOBAL equal to 55° is used. Standard deviation of gradient and profile curvature are now much further from G's than they were in table 7.1. This confirms that the weighting option only makes sense for grid profiles. With the PSBL scheme, the baseline passes through each slope once (or not at all), whether it be long or short. Thus there is no problem of oversampling long slopes relative to short, and the application of weighting in analysis as though this were the case merely distorts the results.

The mean gradient figures of rows 4 and 5 of table 7.1, for large PSBL profile samples with different GLOBAL, show greater sensitivity to terminating conditions than for grid samples. Such sensitivity is undesirable in a method required to stand up to the rigours of field survey. The demonstration in section 6.4 of the scheme's sensitivity to the outcome of difficult decisions made by the investigator in constructing the PSBL in the first place also argues against its use.

7.2 iii Stream and divide profiles

Summary statistics from matrix-based profiles generated from pairs of points 25 m on either side of the stream and talweg (i.e. setting IFSND to 1 in SLOPROFIL.2, see section 6.4 iv) are presented in rows 9 to 11 and 13 and 14 of table 7.1. The stream and divide points were chosen by partitioning the digitized streams and divides into a specified number of equal lengths, as was done also in selecting points along the PSBL (described in chapter 2).

The results in rows 9 and 10 show that summary statistics very similar to the best grid scheme samples can be attained by a divide scheme with much shorter average profile lengths (about 230 m for divide with GLOBAL = 40°, compared with 450-500 m for grid scheme GLOBAL = 40°). The short length of the divide profiles arises because they are not permitted to advance upslope at all from their starting locations, by the algorithm selected by the IFSND = 1 option. This prevents them from following a plunging divide. However, adequate sampling of low-angled divide slopes is ensured by the fact that the profiles start there. Some disagreement in statistics between divide samples and G occurs for standard deviation of altitude, which is inevitable given that an even cover of profiles over the area is unlikely to be achieved: divides are likely to be more numerous in some parts of the catchment than others.

Stream profiles are less successful. Their lengths are here shown to be very dependent on the value of GLOBAL chosen (see rows 13 and 14, table 7.1), as is the case for standard deviation of altitude also. The positions of starting-points were governed by the distribution of blue lines on the 1:25,000 map in this study, and since these did not extend to the head of every topographic low (see the discussion of crenulations in section 6.4 ii), there are bound to be areas impossible to sample from this scheme. Such omissions would most affect the heads of first-order valleys, and such bias may explain why it is difficult to estimate altitude statistics well with this scheme. It should be noted that some topographic lows as indicated by contour crenulations were not marked on the map as containing blue lines at all, and so no divide was constructed around that area, which would therefore affect the ability of divide-scheme profiles to sample there also. Yet this problem is likely to be less serious than for talweg profiles, because the more usual situation was for there to be a blue line marked in a valley, which did not extend to the head of the contour-crenulated line. Such a valley would therefore be guaranteed to receive a divide, but its upper reaches would not be samplable from the blue line.

It was never the intention in this study that stream locations should be used alone to define profile starting locations : rather it was supposed that stream and divide together could make for a viable scheme. The statistics presented here suggest however that divide locations alone <u>can</u> make for successful coverage of the area, gauged by agreement with G's statistics. Were plan curvature to be included in analysis, it is more likely that it would be judged that stream <u>and</u> divide profiles would be needed, since in the previous chapter it was shown that profile deviation due to slope curvature in plan is extreme when profiles are started at either end of a slope.

Figure 7.1 shows the divide profiles whose summary statistics are presented in row 10 of table 7.1, and figure 7.2 the talweg profiles summarized in row 13 of that table. Both figures show the tendency of paired profiles to traverse the same slope rather than opposite slopes as intended, which is a consequence of disagreement between talweg /divide position as indicated by the matrix altitudes and as digitized to define the talwegs/divides used as starting locations. In view of this, some investigators might prefer to generate only one profile AMULT steplengths from each original digitized point. It is possible to do this by inputting a value for IPAIR equal to 1 in a run of SLOPROFIL.2, rather than 2 as used here. Another remedy is to define divides and talwegs from the matrix rather than separately, as is done for Ferro in chapter 9.

A disadvantage of the divide scheme is that results are not stable for the sort of sample sizes (about 20 profiles) that were successful in the grid sample. Row 12 of table 7.1 gives the result of using the same input points on the divide as were used for the run presented in row 10, but only generating a profile from one of the possible pair of locations 25 m on either side of the input point. Mean gradient has been increased considerably by this decrease in sample size from 38 to 19 profiles. As an alternative, every second divide point used in the run in row 10 was used to generate a pair of profiles : results are presented in row 11. This produces a worse result for a 19-profile sample than before, in that standard deviation of gradient also deviates from G's figure : it is evident that for small samples of divide-based profiles, unstable results can be expected. The similarity in the results displayed in rows 9 and 10 of table 7.1 implies that only for a sample size larger than about 40 can divide-based profiles be expected to give summary statistics independent of sample size.

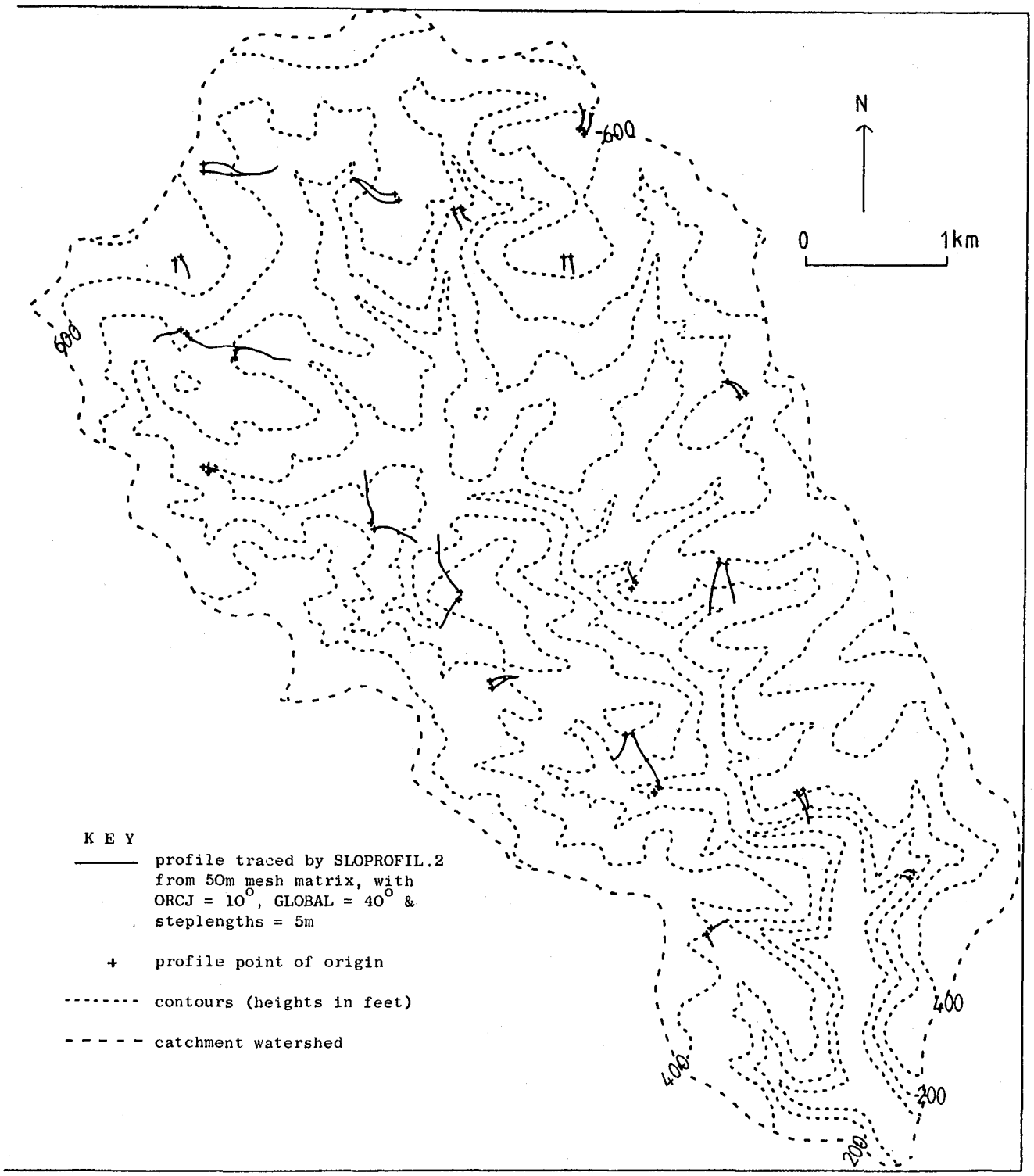


Figure 7.1 : Paired profiles in Gara catchment commencing 25 m either side of divides,and tracing only downslope.

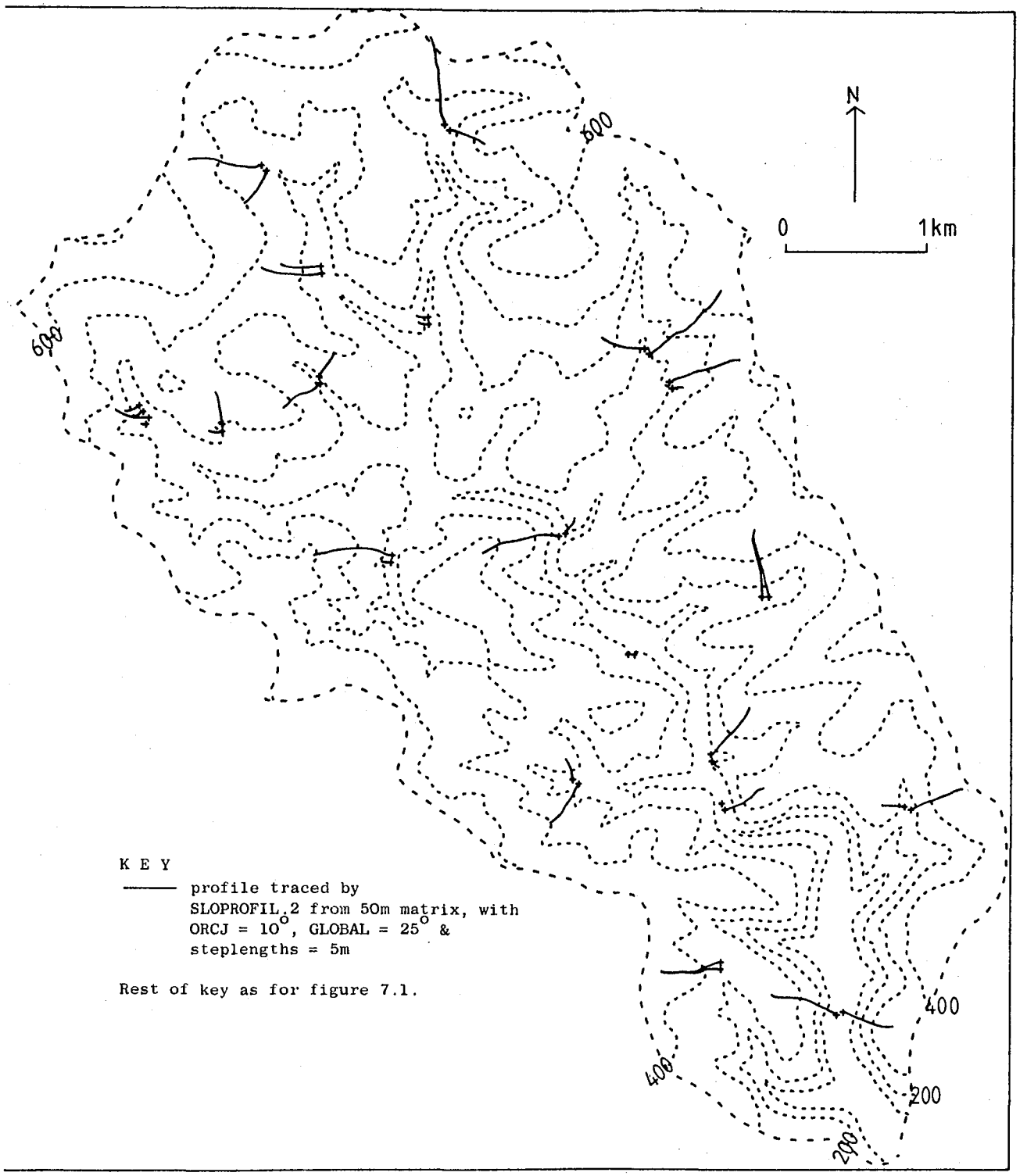


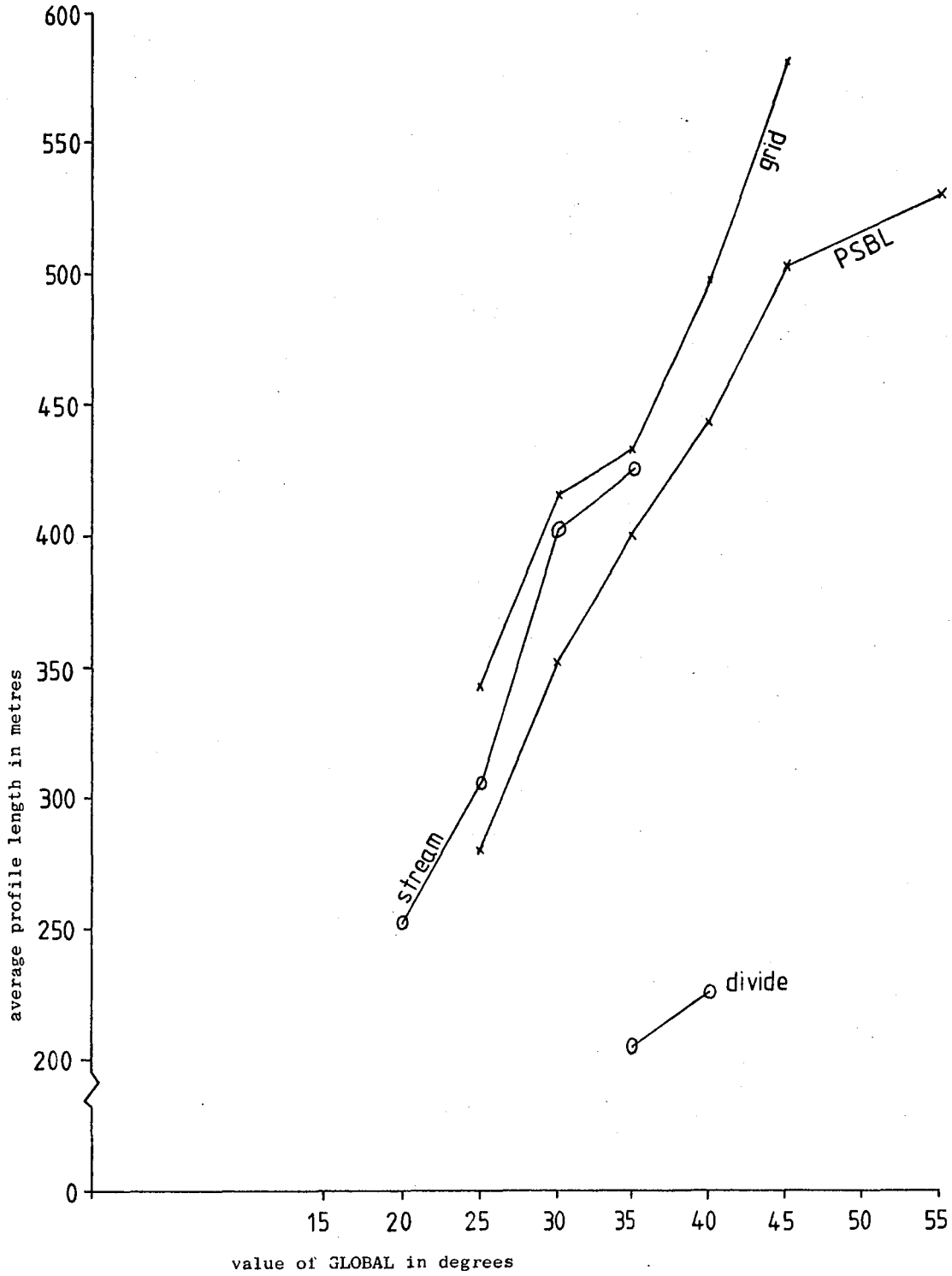
Figure 7.2 : Paired profiles in Gara catchment commencing 25 m either side of talwegs, and tracing only upslope.

7.2 iv Conclusions on a Gara profiling scheme

Figure 7.3 displays the variation of profile lengths with value of GLOBAL used for the sampling schemes. It is immediately clear that the divide scheme outstrips all the others in terms of economy in achieving a successful coverage with short profiles; talweg profiles (if GLOBAL=25° is judged successful) come next, and the grid scheme the last (longest profiles for success, at GLOBAL = 40°). If one wants to avoid much sampling of plunging divides then a divide scheme commencing profiles some distance from the crest (25 m was used here), and proceeding only downslope, would be recommended.

However coverage of the surface would not necessarily be even : in particular, downslope convexities would not be sampled at all. The inclusion of talweg profiles, preferably defined by contour crenulations, would be desirable. A divide or talweg-and-divide scheme seems to have more to recommend it than the PSBL which involves an additional operation after talwegs and divides have been defined, and is executed according to a subjective method.

For maximum ease in generating points of origin, the grid scheme is the best choice. The stability of weighted results over a range of sample sizes generated according to this scheme is also an advantage. Although profiles generated by a grid pattern of points need to be twice as long on average as divide-based profiles, there need be only half the number of them, which is an advantage in practice because it is easier in the field to carry on with a profile than it is to set one up initially.



Sample size in all cases equals 20-40 profiles
Steplengths = 5 m

Figure 7.3 : Graph showing variation of average profile length with value of GLOBAL used in computer profiles located according to various sampling schemes in the Gara.

7.3 Matrix-based profiles in the Netherhearth catchment

In chapter 2 it was noted that there are broadly two types of slope in this catchment : over the high-altitude southern part of the area, the ground slopes northward in a long sweep towards the mouth of the Sike. Lower down in the catchment towards its outlet, the Netherhearth has imposed its own valley system on this regional slope, giving rise to short profiles trending roughly east-west (as did profiles 1 to 14 measured in the field near to the mouth of the Sike, presented in chapter 2).

It was asserted in the previous chapter that no surface-specific scheme for locating profile points of origin (e.g. the PSBL or river and divide schemes) would be viable in this catchment because of the lack of dissection. The surface-random patterns (grid or random location of points of origin) which must therefore be implemented here have in common that they give an equal chance of selection to all areas in the catchment. This leads them to oversample long slopes because profiles are longer on these slopes. Since this catchment is characterized by two sub-populations of slopes of very unequal lengths as described in the previous paragraph, it is impossible to reproduce matrix-G's statistics with data from profiles in this area unless weighting is used in analysis as was described in section 7.2 i.

Row 1 of table 7.3 presents the result of unweighted analysis from a grid pattern of profiles generated on computer for the area, with ORCJ = 10° and GLOBAL = 35°. It is clear from the altitude statistics (compared with matrix-G figures, row 14 table 7.3) that sampling is heavily biased towards the high-altitude slopes, which is confirmed by an inspection of figure 7.4 showing profiles generated by a grid pattern of points of origin over the area. The application

Table 7.3 : Summary statistics for matrix-based profile samples in the Netherhearth catchment

(Underlined if matrix-G value + 2 % ≥ profile value ≥ matrix-G value -2 %)

Design	ORCJ	GLOBAL	No. of profiles	Step-length (m)	Altitude (m) mean	Altitude st.dev.	Altitude skew	Gradient (°) mean	Gradient st.dev.	Gradient skew	Profile curvature (°/100m) st.dev.	Profile curvature skew	Average profile length (m)
1) grid*	10°	35°	26	5.0	661.96	44.60	-0.15	7.51	3.07	0.42	20.37	-0.75	66.15
2) grid	10°	35°	26	5.0	647.10	51.81	0.34	7.40	3.22	0.35	26.23	-0.79	66.15
3) grid	40°	90°	123	5.0	648.70	49.57	0.91	5.91	2.95	0.65	24.61	-0.41	172.40
4) grid	50°	90°	126	5.0	647.91	49.46	1.03	5.70	3.02	0.68	24.73	-0.39	182.95
5) grid	60	90°	127	5.0	648.10	49.34	1.06	5.58	3.03	0.70	24.51	-0.42	189.35
6) grid	40°	90°	32	5.0	647.66	50.76	0.60	6.12	3.24	0.78	25.53	-0.52	165.78
7) grid	50°	90°	32	5.0	647.26	50.16	0.58	6.09	3.31	0.86	25.81	-0.45	167.35
8) grid	60°	90°	32	5.0	647.40	50.17	0.59	5.99	3.29	0.88	25.41	-0.42	170.80
9) grid	60°	90°	32	1.5	647.63	49.92	1.10	5.47	3.47	0.86	37.75	-0.51	198.05
10) grid	60°	90°	32	1.5 interpolated	as for row (8)			5.80	3.36	0.84	38.21	-0.82	as for row(8)
11) random	60°	90°	33	5.0	655.40	51.02	0.31	5.41	3.05	0.43	26.50	-0.18	164.55
12) random	60°	90°	24	5.0	656.42	53.13	0.42	6.53	3.93	0.70	29.18	-0.88	161.65
13) grid	60°	90°	19	5.0	655.71	55.19	0.24	6.50	3.58	1.16	31.79	-0.34	216.30
14) matrix, 10m mesh					645.21	49.77	0.49	5.95	3.10	0.64	28.32	-0.68	

* All samples except those marked with asterisk were analysed with weighting attached to each steplength equal to reciprocal of number of steplengths in profile.

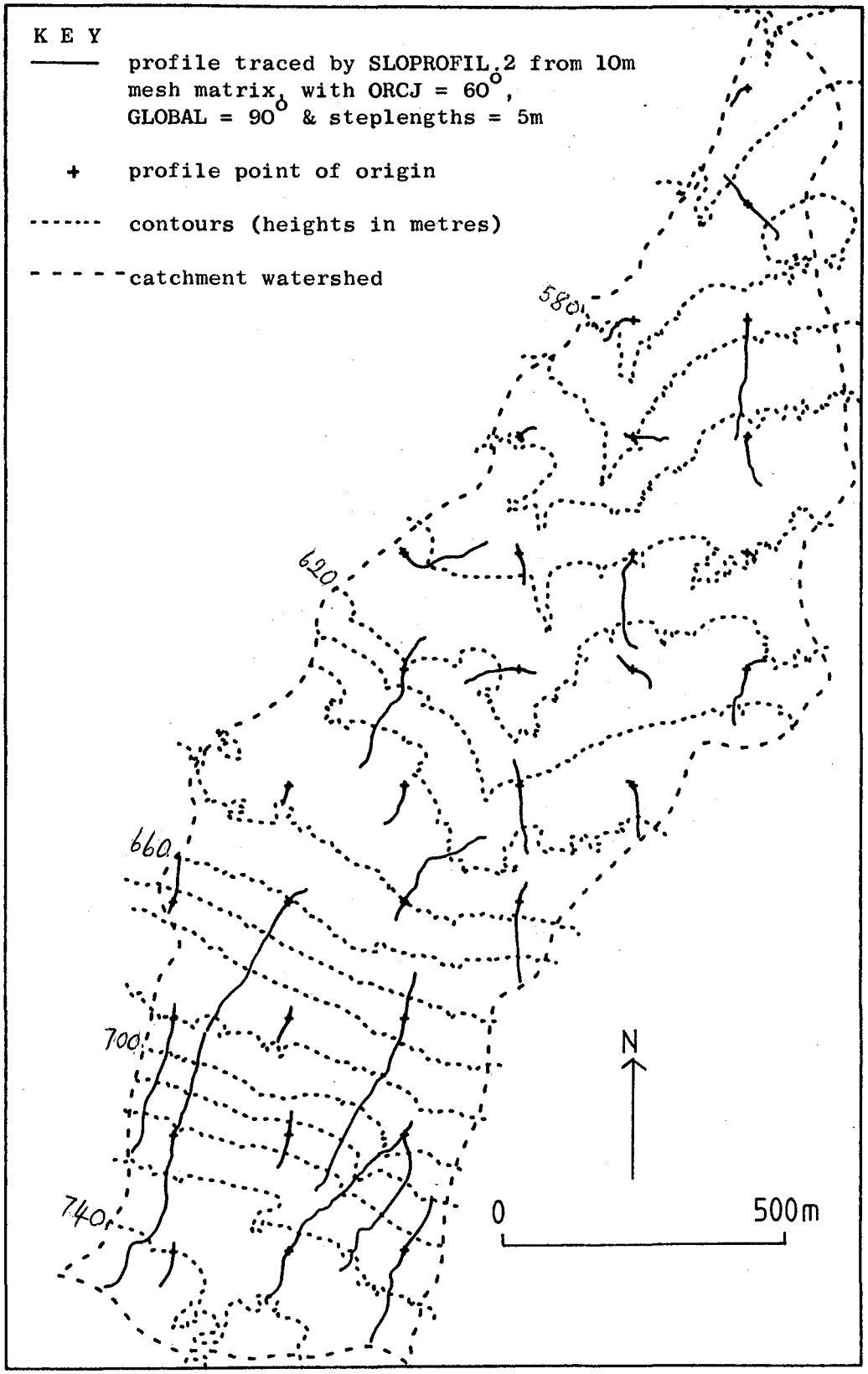
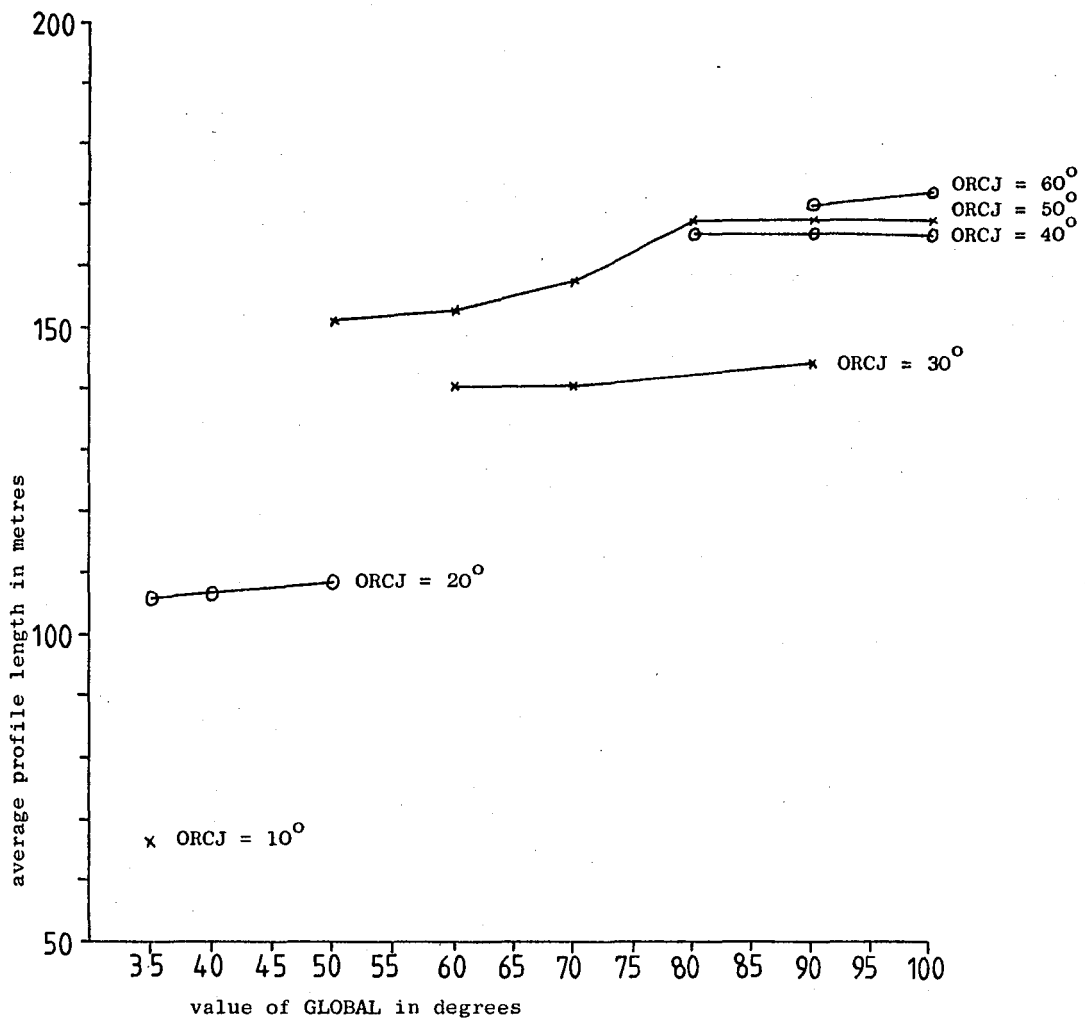


Figure 7.4 : 32 profiles located according to a grid pattern of points of origin in the Netherhearth catchment.

of a function which gives equal weight to profiles rather than to individual steplengths produces a set of altitude statistics in better agreement with the G sample,as is shown in row 2 of the table. However the figure for mean gradient in row 2 is still a long way off matrix-G's, making it clear that, though successful for the Gara, the terminating conditions ORCJ = 10° and GLOBAL = 35° are too strict for the Netherhearth catchment.

It was found in the Netherhearth that increasing the value of GLOBAL had practically no effect on mean profile lengths and summary statistics. By contrast profiles were sensitive to the value of ORCJ chosen, as is made clear in figure 7.5. Here it can be seen that for low values of ORCJ (20°, 30°), increasing the value of GLOBAL to a high figure of 90° has little effect on profile lengths. By contrast a change in ORCJ from 20° to 30° produces an increase in average profile length of about one-third. For higher values of ORCJ (50°), there is some increase in profile lengths as GLOBAL values are increased from 50° to 80°, but after that a plateau is reached in the response of profile length to GLOBAL. The process of profile lengthening cannot go on indefinitely : hence the clustering together of the higher ORCJ curves in figure 7.5 (ORCJ = 40°, 50°, 60°). At greater values of ORCJ and GLOBAL, one finds more profiles terminating according to terminating condition 6 of SLOPROFIL.2 (explained in section 4.3),which often means that they have reached a local summit so that to go any further would require a reversal in slope angle.

There is thus a contrast between Gara and Netherhearth catchments : the former is characterized by smooth slopes whose orthogonals undergo only gradual changes in bearing as they ascend a slope curved in plan, so that the value of GLOBAL is important to stop a profile continuously curving on towards the summit of the watershed. By



Sample size in all cases equals about 30 profiles.
Steplengths = 5 m.

Figure 7.5 : Graph showing variation of average length of Netherhearth profiles generated from a grid pattern of points of origin with different values of ORCJ and GLOBAL.

contrast, the topography of the Netherhearth is much more uneven : this is due to the relatively chaotic drainage of areas of eroding peat, and to use of a detailed matrix of the area at 10 m mesh which captures this variability.

The aim is still to find a profile sample for the Netherhearth that will give agreement in summary statistics with the systematic sample of values from matrix-G. In rows 3, 4 and 5 of table 7.3 the results of large samples of grid profiles generated with different values of ORCJ are presented. Greatest agreement with G's mean gradient is achieved by a scheme having ORCJ = 40°. Results from smaller grid patterns of matrix-based profiles generated according to the same terminating conditions are presented in table 7.3, rows 6 to 8 inclusive. They contradict the results of the larger samples, in favouring a scheme with ORCJ = 60° to produce a mean gradient figure like the matrix's with G. This would appear to be discouraging because the sample size for the runs that produced the statistics in rows 6 to 8 was not small (32 profiles), so the lack of agreement between these and substantially larger profile samples would suggest that a lot of profiling would need to be done in the field. Yet it seems contrary to common sense to suggest that a catchment about a twentieth of the size of the Gara should need a sample of profiles twice the size.

The apparent conflict can be resolved by looking at the figures for mean profile length (right-hand column, table 7.3). The large sample with ORCJ = 40° (row 3) produces a similar length of profile to the smaller sample with ORCJ = 60° (row 8), at just over 170 m. The other two large profile samples (rows 4 and 5) generated profiles 10 and 17 m longer than these on average, which could be expected to make a considerable difference to the coverage of the surface being achieved with so many profiles.

How identical terminating conditions can produce such different profile lengths for different sample sizes is an interesting question : it must be that with a larger sample one is more likely to hit on locations on the long regional slope area in the south of the catchment from which profiles can be sustained without large bearing deviation for a considerable distance. The important point is that an investigator can settle on the sort of average profile length that gives agreement with G's mean gradient, and then if necessary tailor terminating conditions to fit the profile sample size to be used. In the Gara catchment this latter was not necessary, as the same terminating conditions were found to give results similar to matrix-G's for small and large sample sizes.

So far no mention has been made of standard deviation of gradient and profile curvature. The latter in particular is noticeably underestimated by the matrix-based profiles, in marked contrast to the situation for the Gara. However this is again due to the more detailed grid mesh of the Netherhearth matrix. In row 9 of table 7.3 the result is shown of using a steplength for Netherhearth profiles of approximately a tenth the size of the grid mesh, as was the case in the Gara when using 5 m steplengths. This causes the standard deviation of profile curvature to increase by half as much again : a considerable change. In fact the statistics in row 9, produced by a run of SLOPROFIL.2 using 1.5 m steplengths, are not directly comparable with those in row 8 because the use of shorter steplengths in the former case produced profiles 27 m longer on average,despite use of the same terminating conditions. This was presumably because taking shorter steps allowed a profile to negotiate a change in slope orientation more gradually than is possible with a 5 m steplength, and so avoid triggering termination due to ORCJ in some cases. To produce short-steplength

profile data directly comparable with row 8, the profile readings summarized in row 8 were taken and 1.5 m horizontal constant lengths interpolated from them. The result, in row 10 of the table, shows that mean gradient is fairly insensitive to the change in resolution. Standard deviation of gradient is increased by a small amount, while standard deviation of profile curvature is greatly altered. This is direct evidence then for the dependence of this statistic on the scale of measurement, a topic dealt with further in the next chapter.

To consider a random scheme for locating points of origin : row 11 of table 7.3 presents the result of generating a similar number of profiles (33) located by random number tables. Mean and standard deviation of gradient are closer to those estimated by the large grid ORCJ = 60° scheme (row 5) than are these statistics from the smaller grid sample with ORCJ = 60° (row 8), a point in favour of the random scheme. However the altitude statistics show that an even coverage of the catchment is not being achieved, as one could have predicted by looking at the distribution of profiles shown in figure 7.6. A problem with randomly-located profiles is that results from them are likely to be very dependent on luck with the distribution of points, unless a very large sample is taken to ensure good areal coverage. Row 12 of table 7.3 presents results from a different set of randomly-located profiles. The profile sample size is smaller, but mean gradient is more than tolerably higher (by more than 1°) than from the previous random sample with the same terminating conditions.

The results in row 13 show that grid profiles too are not immune to the vagaries of profile location in this catchment : these 19 profiles were produced by taking the origin of the grid used to locate points of origin at the same matrix vertex as was used for all the other grid runs displayed in table 7.3, but using a wider

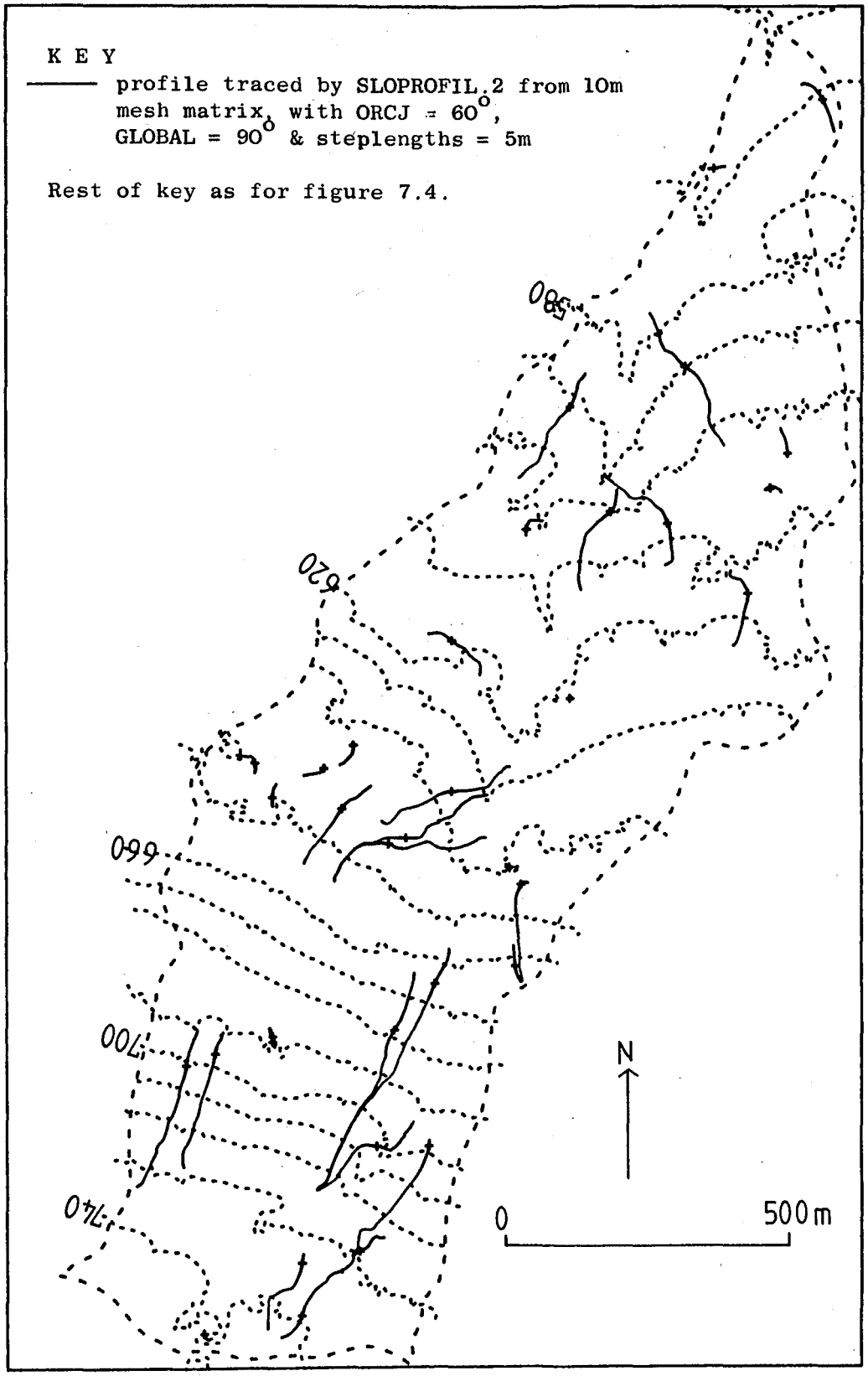


Figure 7.6 : Profiles located according to a random pattern of points of origin in the Netherhearth catchment.

spacing of grid. Mean gradient has been increased by 0.5° compared with the 32-profile grid sample with the same terminating conditions (row 8). Part of the problem with sampling the Netherhearth catchment with the grid applied here is that the land forms exhibit east-west lineation (e.g. see contours on figure 7.4), which closely parallels one of the grid directions. In addition, the narrowness of the northern part of the catchment means that the exact positions of grid intersections can make the difference between this area being well represented and hardly at all. The high mean altitude figure in row 13 implies that the latter was the case in this sample; figure 7.7 (showing the profiles generated in this run) confirms this (the high-altitude part of the catchment had 8 profiles as against 5 in the low-altitude north). Random location of points of origin could produce coverage more uneven than this. The high mean length for these grid profiles is another consequence of oversampling the south of the catchment.

For the large grid profile runs (rows 3 to 5), high mean profile length was associated with lower mean gradient however. This is another case of small-sample results not being consistent with large. Figure 7.8, plotted from the results of one batch of matrix-based profiles, shows that there is not a consistent relationship (Pearson's product-moment correlation coefficient being only 0.188) between profile length and profile median gradient. (Median gradient was used here to obtain a figure resistant to the influence of large outlying gradient values caused by localized relief features). While it is certainly true that the high-altitude south of the catchment has steeper slopes (see the contoured maps, e.g. figure 7.4), not all profiles generated on these are long; and similarly the slopes on the low-gradient northern section of the catchment are not all short, especially where

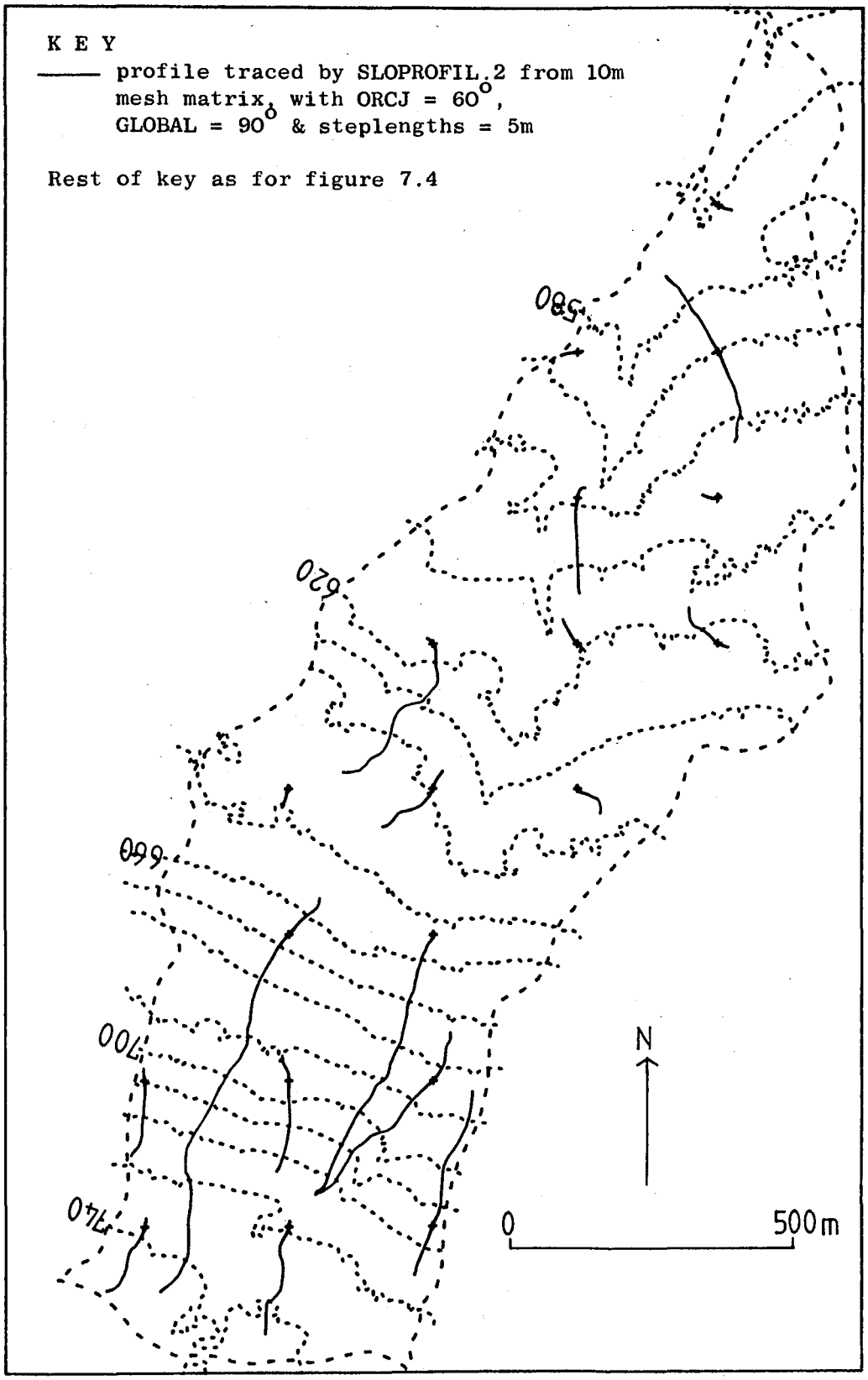


Figure 7.7 : 19 profiles located according to a grid pattern of points of origin in the Netherhearth catchment.

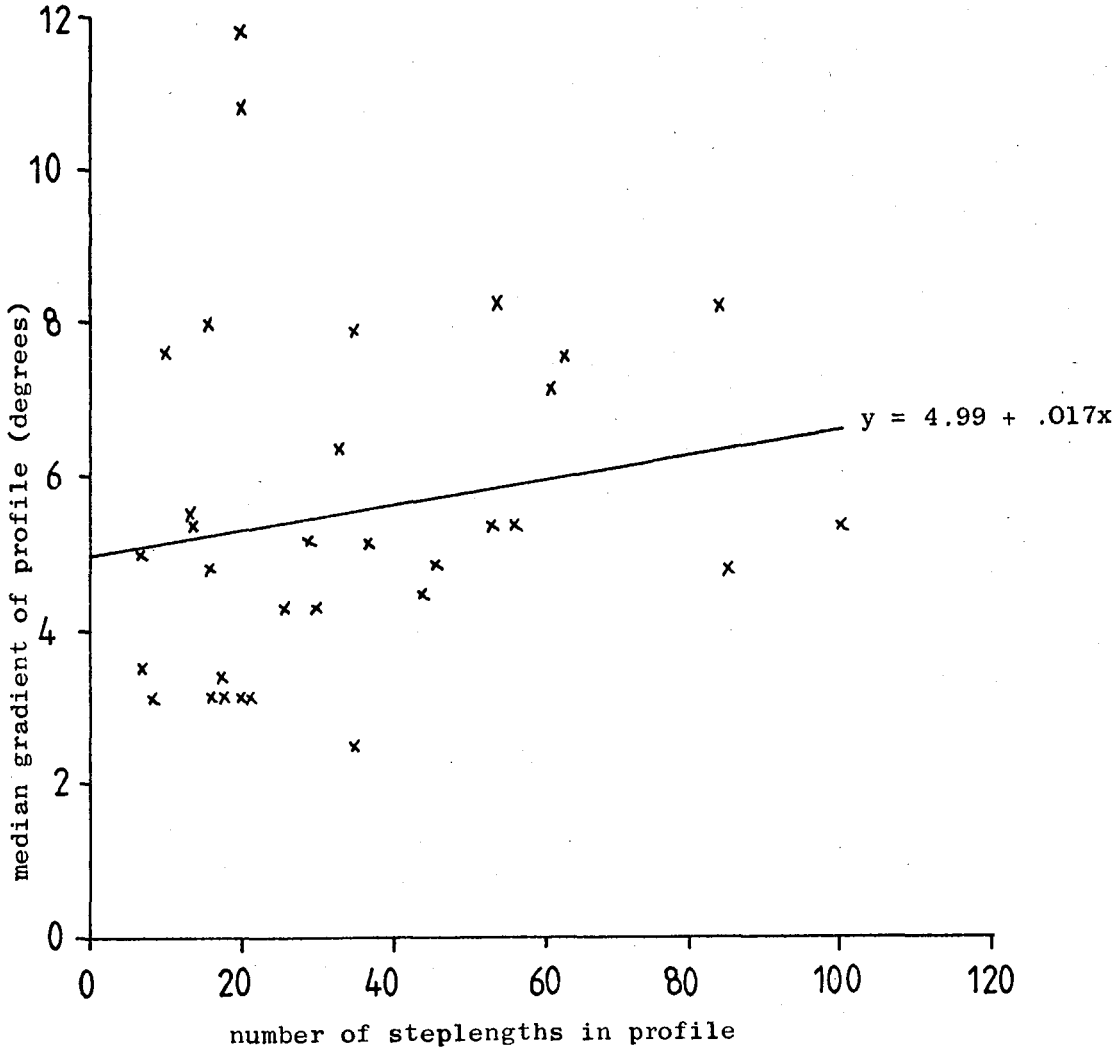


Figure 7.8 : Regression of median gradient on length of profile for the profile set depicted in figure 7.4.

they start some way from the main Sike valley. How sustained a profile can be in either part of the catchment depends very much on its location relative to a minor talweg, and this is what makes a good profile survey difficult to achieve here.

To obtain a profile sample with the desired properties in the field, one would have to locate the points of origin of a profile design found successful on computer fairly accurately, despite the bad weather conditions of the area described in chapter 2. This would be easiest with a grid scheme, because the surveyor need locate only one point in the net accurately - which could be done by sighting onto the Great Dun Fell masts and Moor House field station during a bright spell - and from it the other points could be determined by pacing with compass along the grid directions.

Figures 7.4, 7.6 and 7.7 show clearly the situation that was noticed in the field and reported in chapter 2, that the Sike's valleysides only extend for some distance to its east and west, while beyond that the regional slope towards the north takes over even near the Netherhearth's mouth. The continuation of profile measurement up to the watershed along the path established lower down the profile (as is recommended practice in Young's 'perpendicular extension procedure') would produce a large number of useless measurements perpendicular to true slope : the Pitty method, of profile cut-off at the point where true slope is no longer in the direction of the profile line, is much more sensible here (these terms were introduced and referenced in chapter 2). Summits do not go unsampled with the cut-off method, because an even coverage of points of origin ensures that some profiles follow the plunging divide above the Sike's valley. It is not necessary in profiling ever to compromise the condition of orthogonality to contours, as success with SLOPROFIL.2 proves.

7.4 Implications of restriction to 'slopes relatively straight in plan'

It was mentioned in chapter 2 that restriction to slopes relatively straight in plan is common among profilers, primarily for reasons of ease of survey. Thus Carter and Chorley (1961) excluded first-order hollows from survey because of difficulty in locating their orthogonals, and Pitty (1966, 1969) excludes all profiles that cannot be measured along an approximately constant bearing because he claims that only in that way can a geomorphologist be sure when the slope crest has been reached (quoted in chapter 2). Rapp (1967), Young (1970), Nieuwenhuis and van den Berg (1971), Parsons (1973, 1978), Abrahams and Parsons (1977), and Cox (1979) are some of the many profilers who have restricted survey to slopes straight in plan. Blong however stated that such a restriction 'would, in fact, be undesirable as many surveyed maximum slope profiles have some down-valley curvature' (1972, 188).

In many studies it is not the aim to obtain an areally representative profile sample, but for those where it is, this study can demonstrate with SLOPROFIL.2 the statistical consequences of such a restriction in the Gara catchment, a fairly typical part of south-west England. Figure 7.9 shows profiles resulting from a grid sample of profiles generated by SLOPROFIL.2 with ORCJ = 10° and GLOBAL = 30°, and figure 7.10 those from a PSBL sample with ORCJ = 10° and GLOBAL = 40° using 5 m steplengths on the 50 m mesh matrix - in both cases the terminating values used were those found to give results most like the matrix with G in unweighted analysis (giving each steplength a weight of 1). The two samples contained around 135 profiles each, a sample judged to be large enough to avoid idiosyncracies of location.

Figures 7.9 and 7.10 were plotted on a contour map of the Gara at a detailed scale. Then, taking each profile in turn, the contours

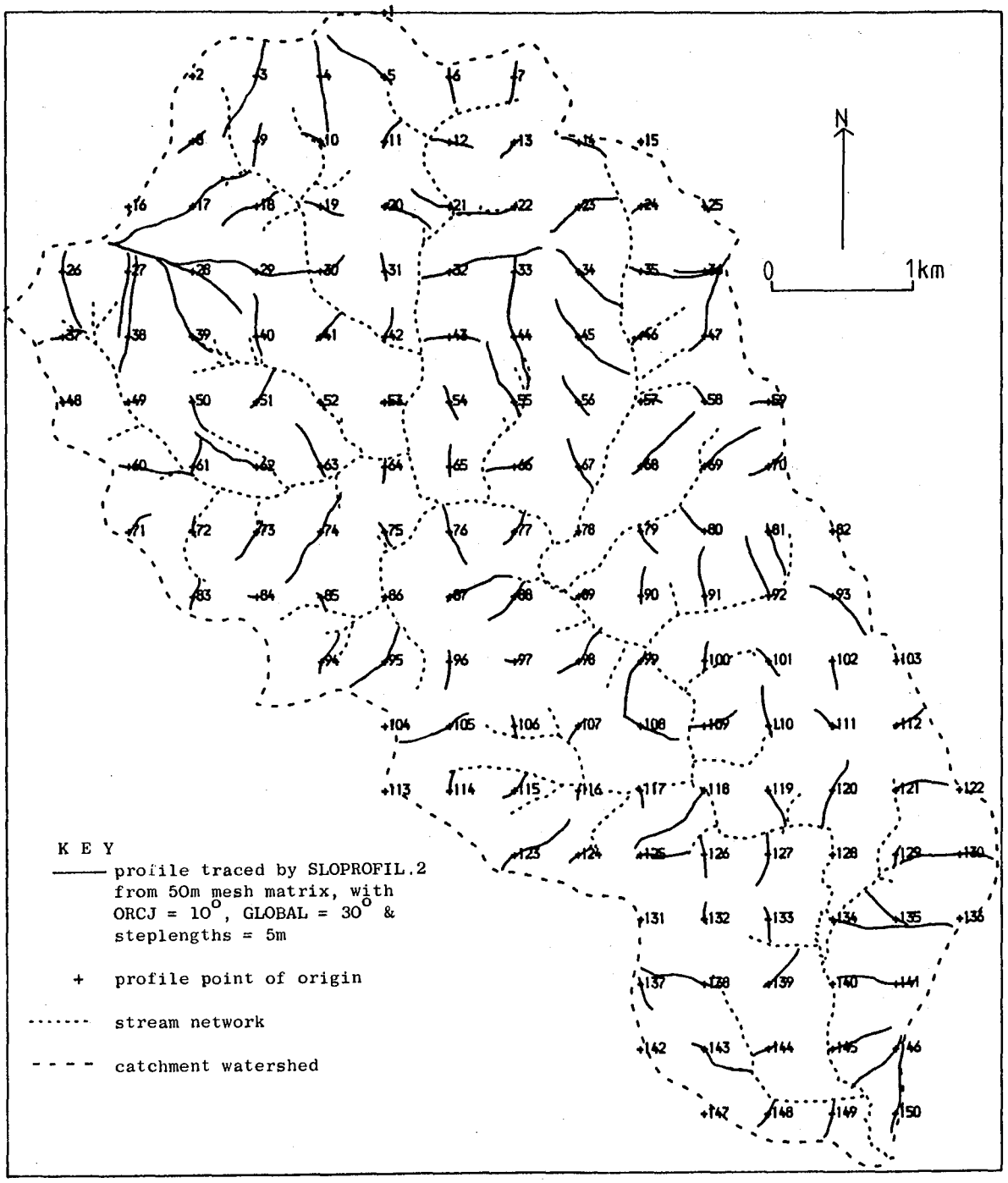


Figure 7.9 : A large grid sample of profiles in the Gara catchment, including profiles traversing slopes not relatively straight in plan.

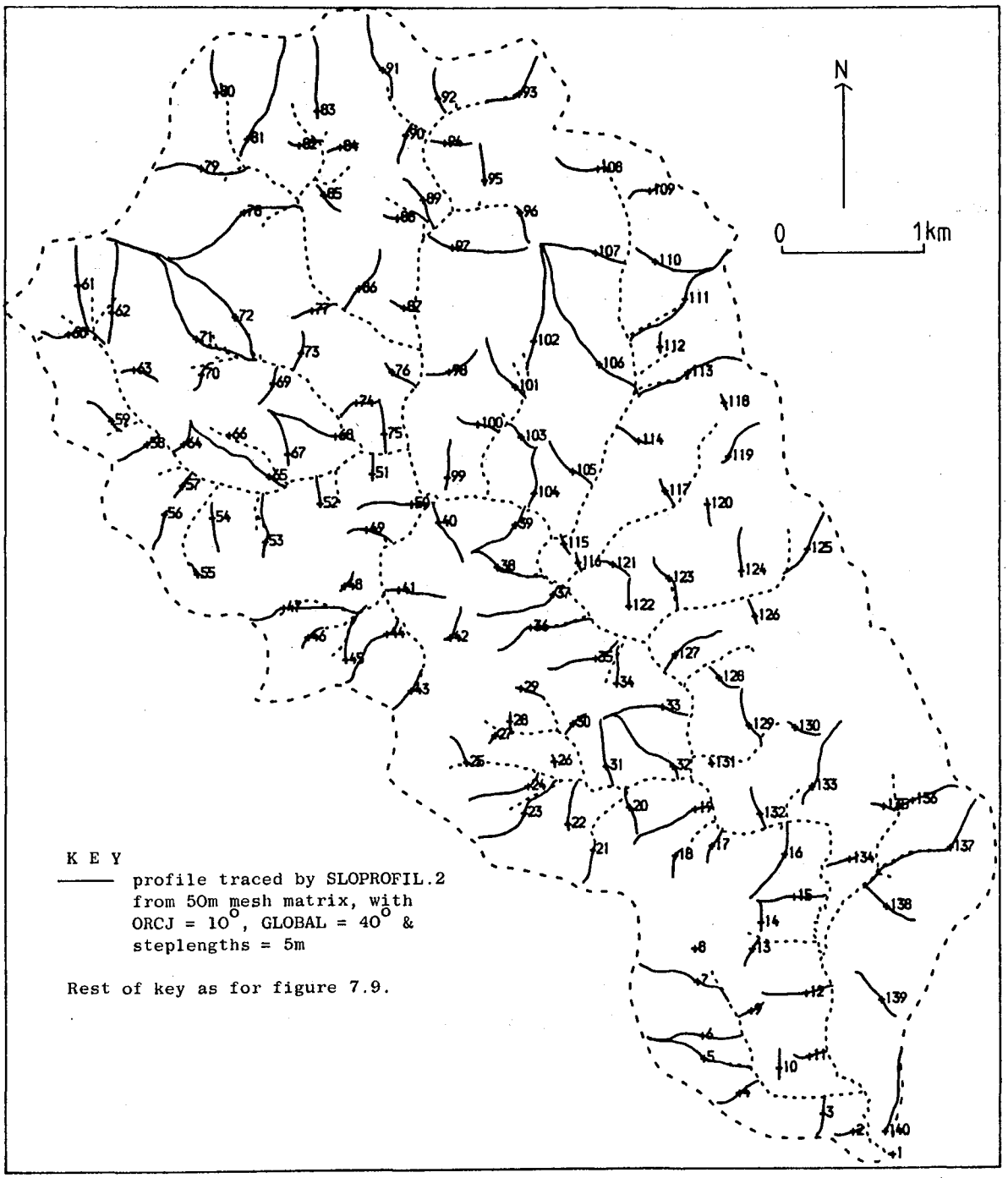


Figure 7.10 : A large sample of Gara profiles located along the PSBL, including profiles traversing slopes not relatively straight in plan.

of the slope it traversed were examined to determine whether they were 'relatively straight in plan'. The procedure for this determination was as recommended in Young (1974) : on a piece of tracing paper two lines of length equivalent to 100 m on the ground are drawn, joined at one end and at an angle of 150° to each other. This is placed over the contour nearest to the steepest part of the slope traversed by the profile, and 'If the contour beneath the ends of the template lines is inclined by less than the template lines, the slope is relatively straight in plan' (ibid., 14). The profiles found not to traverse slopes relatively straight in plan were excluded from the sample, while the rest were replotted in figure 7.11. An examination of the relations between stream and profile locations on figure 7.11 shows that profiles are preferentially excluded from stream head areas, particularly those of tributaries nearer the mouth of the catchment, having deep and rounded valley-head hollows. This is confirmation of what was expected : that the restriction tends to exclude from measurement the valley head areas, which are so important hydrologically.

In table 7.4 the results of the complete grid and PSBL samples are presented together with summary statistics from the two restricted samples. The figures for mean gradient show quite unambiguously that the restricted sample is preferentially excluding some low-angled slopes, which comparison of figure 7.11 with figures 7.9 and 7.10 has shown to be the slopes at the heads of first order tributaries. The standard deviation of gradient has increased, perhaps because the slopes that tend to be included in the restricted sample are the extremes : particularly the steepest, mid-valley slopes (which include some coverage of low-angled summit areas), and some gentler slopes in the north of the catchment. Standard deviation of profile curvature

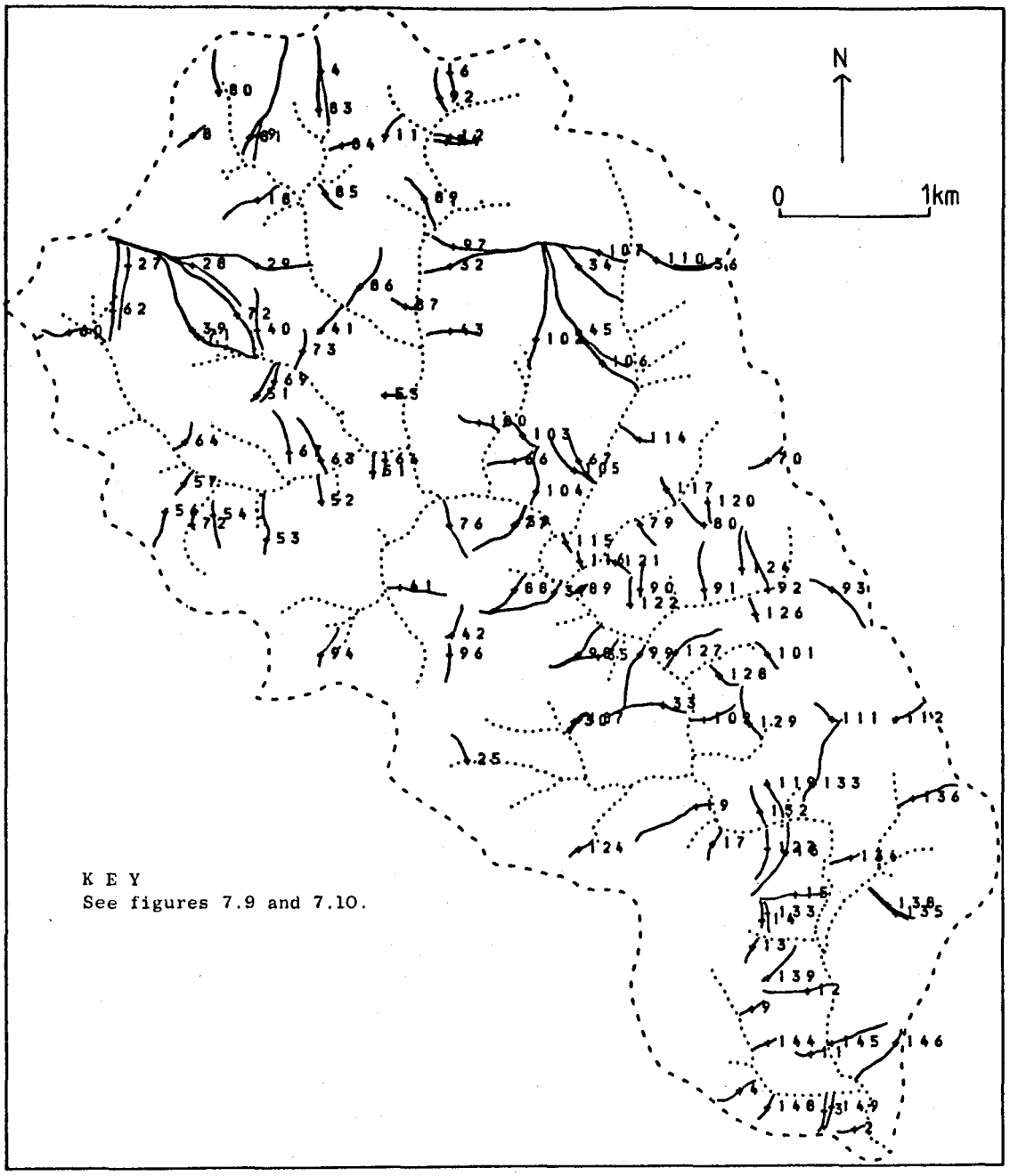


Figure 7.11 : Profiles from figures 7.9 and 7.10, excluding all those traversing slopes not relatively straight in plan.

Table 7.4 : Summary statistics from grid and PSBL scheme profiles in Gara catchment, showing statistical effect of restriction to slopes relatively straight in plan

	Altitude (m)			Gradient (°)			Profile curvature (°/100 m)		Average profile length [m]	No. of profiles
	mean	st.dev.	skew	mean	st.dev.	skew	st.dev.	skew		
Grid, ORCJ = 10° & GLOBAL = 30°, (all profiles)	128.41	40.53	-0.31	7.45	4.70	1.36	10.62	-1.62	380.34	134
Grid, ORCJ = 10° & GLOBAL = 30°, (only profiles on slopes relatively straight in plan	126.87	44.18	-0.15	8.25	5.43	1.23	12.10	-1.91	393.21	56
PSBL, ORCJ = 10° & GLOBAL = 40°, (all profiles)	122.17	39.43	-0.06	7.41	4.98	1.57	11.66	-1.59	425.66	137
PSBL, ORCJ = 10° & GLOBAL = 40°, (only profiles on slopes relatively straight in plan)	123.99	42.94	-0.05	8.10	5.82	1.44	13.17	-1.65	420.64	70

Note: Steplengths for all profiles are 5 m (measured horizontally)

is also increased by the restriction in grid and PSBL cases. This must be because fewer gently-sloping tributary source areas are being sampled. The effect of the restriction is not particularly clear in the altitude statistics, because of the complication that altitude increases from south to north as well as up any one slope in the catchment. The spread of profiles over the catchment ensures a fairly accurate estimation of the matrix-G statistic in all the cases. Estimation of average profile lengths is also relatively resistant to effects of the restriction.

The results of this investigation are clear : that the restriction of measurement to slopes relatively straight in plan will lead to biased coverage of a landscape in which many streams start in rounded valley head areas, as is common for dissected topography in the British Isles. These results suggest that such slopes are gentler in gradient and less curved in profile than the straight valleyside slopes which are well represented in the restricted samples. A number of other profiles in locations with curved contours were also excluded in the restricted sample, complicating interpretation somewhat : the statistics confirm however that the restricted samples were a biased representation of the parent population in both grid and PSBL cases.

7.5 Some comments on appropriate density of profile sampling

From the profile data established by the surface-representative method applied in sections 7.2 and 7.3, further statistics of the sort discussed by Parsons (1982) and mentioned in chapter 1.2 can be calculated which relate more specifically to profiles. The findings of this study contrast with that of Parsons, who found that 'very intensive sampling is required if values are to be obtained that adequately reflect average conditions of form for a drainage basin as a whole' (p.77). Some additional comment needs to be made here on Parsons' conclusion.

Parsons calculates required profile sample sizes from the variance of each attribute measured in a pilot survey, according to a statistical formula (that of Cox, 1952). He concludes from examination of some spatial relations, including autocorrelation between adjacent profiles along a Profile Sampling Baseline, that for several attributes this assumption of spatial randomness cannot be refuted for profiles spaced 200 m apart. He does not however investigate the fact noticed here in the Gara catchment (quoted in section 2.14) that slopes in similar settings (e.g. separate first-order basins in the north of that catchment) are similar. Nor does he investigate the possibility of non-linear relations between variables in space. It seems unreasonable to use formulae which assume a random distribution of attributes when dealing with drainage basin topography having obvious properties of persistence in space, even if these aspects of persistence do not pass the rigours of a significance test in correlation. In geomorphometry we are dealing neither with perfect mathematical surfaces nor with chaos.

It is very likely that if one is interested in profile data for the calculation of detailed land form attributes such as the percentage of profile length from -2 to +2° (to quote an example from Parsons), a more intensive sampling is required than for adequate estimation of mean gradient. An investigator could generate samples of different numbers of profiles all found to be surface-representative by comparison with G, and go on to investigate stability in chosen profile attributes with sample size from them. If more than the 20 to 30 profiles per catchment found necessary here were needed, they could easily be generated on computer. This ease allows one to do away with the necessity to fall back on equations predicting theoretical optimum profile sample sizes like Cox's (1952), which were not developed

for topographic surfaces. The mean of one of Parsons' attributes, profile length, was found from this study to be as well estimated from 32 as from 123 profiles in the Netherhearth catchment.

As an example of possible areas of study opened up by SLOPROFIL.2, a sequence of profiles densely spaced along the PSBL in the Gara was analysed to determine autocorrelation of profile length and of profile average angle at various lags (as set out in Richards (1979)). The results are shown in figure 7.12. For average angle, the finding is unequivocal : the further away profiles are from each other (up to the 700 m maximum investigated here), the less correlated are their average angles. Even at this distance however, the correlation is greater than 0.75. Strahler (1950a) recommends profile sampling at intervals along a slope equal to one-third to one-half of the slope length, to obtain orthogonals that would be followed by 'relatively independent threads of debris movement'. This investigation has shown that profiles far enough apart to be free from mutual interference defined by Strahler's criterion (these slopes were about 400 m long on average), cannot be considered to have come from statistically independent populations as regards overall inclination.

Correlation of profile lengths shows some decline with increasing lag on figure 7.12, but there are notable reversals of this trend. This must be partly due to the fact that profiles on opposite sides of a valley are likely to be similar as well as profiles adjacent to each other on one valleyside. Thus in the Gara there are at least two types of 'adjacency' to be considered in profile studies. It is outside the scope of this study to continue much further in this vein : this thesis can do no more than develop a method and point to its applications. The important point is that the freedom to generate many profiles on computer allows geomorphologists to

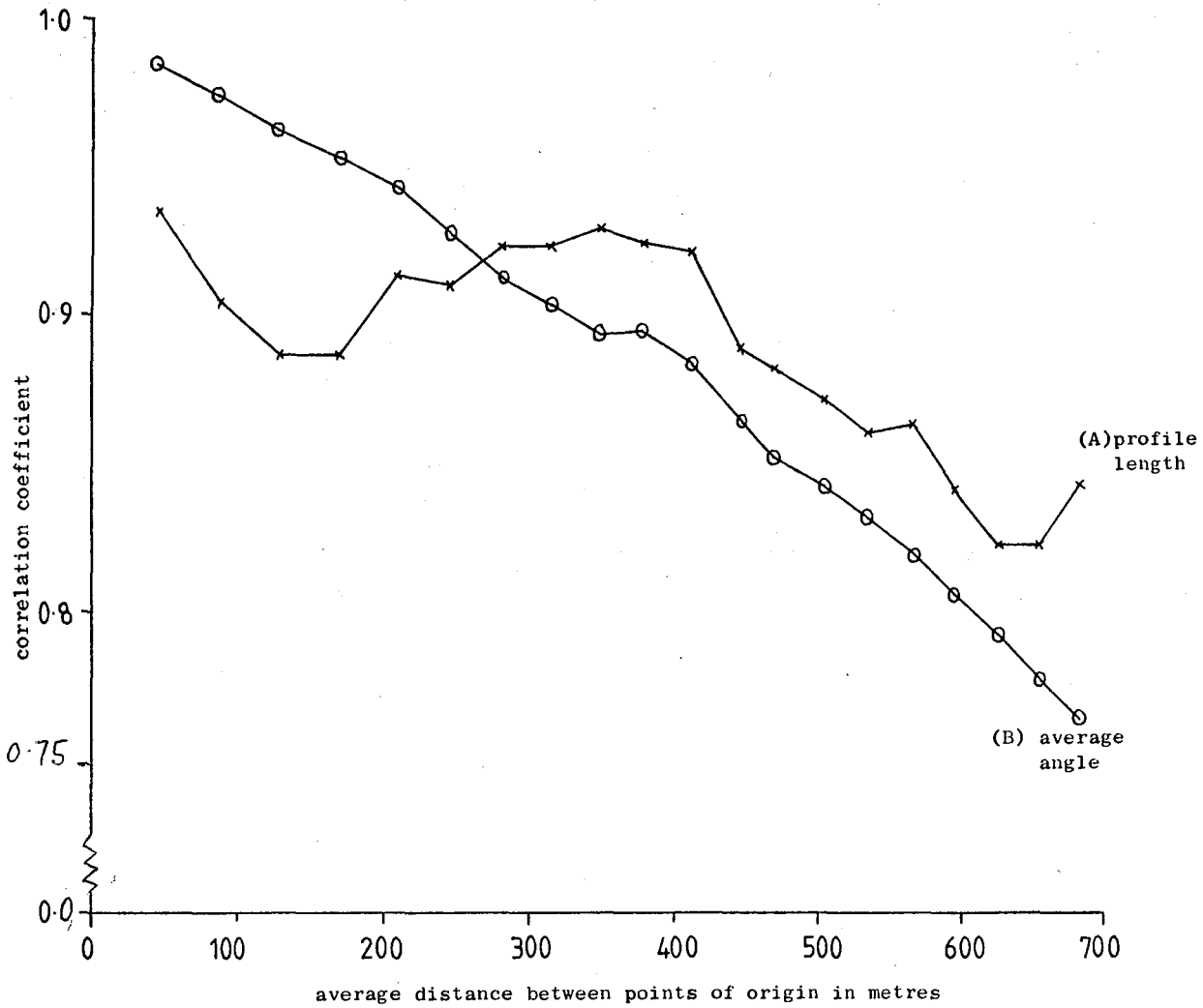


Figure 7.12 : Graph showing autocorrelation of (A) profile length and (B) average angle as a function of average distance between profile points of origin, for a set of 95 PSBL profiles spaced at intervals of 44 m in the south-west of Gara.

quantify the persistence of land form attributes in space that makes geographical samples so different from statistical samples of independent observations.

7.6 Conclusions

The results presented in this chapter have shown that the grid scheme for locating profile points of origin can generate profiles whose summary statistics give a satisfactory representation of selected statistics from the matrix analysed with G. If several grid scheme profiles are to be analysed, they require use of a simple weighting function such that each profile receives an equal weighting; otherwise long slopes will be over-represented in the results. The grid scheme is the only satisfactory method of locating points of origin which is applicable in both the Gara and Netherhearth catchments, which is a great advantage. Random location of points of origin has no advantage over a grid scheme, and produces unpredictable results unless one is prepared to use a large profile sample, because spatial coverage of the surface by points of origin is unpredictable.

Of the other possible schemes for locating profile points of origin, a system of paired or single profiles starting some way from divides and talwegs (25 m was found best for the Gara) has much to recommend it in topography sufficiently well-dissected for divides and talwegs to be drawn in without too much difficulty. This is therefore not a viable option in the small eroding peat catchment of the Netherhearth.

The construction of the PSBL involves an additional operation in defining a line mid-way between divides and talwegs. It thus has the disadvantages of a divide and talweg scheme(i.e. it cannot be applied in a catchment such as the Netherhearth), and the substantial additional

drawback of subjectivity in construction of the PSBL itself. Its supposed advantage - of avoiding oversampling of downslope concavities and upslope convexities, and undersampling of the converse - is difficult or impossible to realise in a landscape of plan-curved slopes, as was shown in the previous chapter. In order to achieve coverage of an entire surface, the PSBL must penetrate deeply into upslope concavities and downslope convexities, making over-sampling of first-order valleys unavoidable. This bias is too complex to be remedied by any statistical correction analogous to length-weighting for grid profiles.

The PSBL, and any other scheme for that matter, could generate a set of profiles to sample slopes relatively straight in plan quite acceptably. Yet this common restriction in profile measurement has been demonstrated in section 7.4 to produce biased estimates of surface attributes for the Gara catchment which, like many British catchments, is characterized by valley-head concavities. The bias amounts to an oversampling of steeper slopes along the valley sides below the headwater areas, and results in the exclusion of 54% of the profiles depicted in figures 7.9 and 7.10.

The analysis has concentrated on achievement of comparability between profiles and matrix-G for all altitude statistics and mean gradient. Less attention has been paid to standard deviation of gradient, and least attention of all to standard deviation of profile curvature, as these are influenced by scale and method of measurement (as will be discussed further in the following chapter). The sensitivity of altitude statistics to profile locations, and of mean gradient to terminating conditions (and hence profile length), shows that by these comparisons alone the sampling design and lengths of profiles to be surveyed in the field can be decided first by comparison with

surface-wide statistics on computer. Such comparison has not previously been attempted by profilers to this writer's knowledge.

This study has made abundantly clear the importance of the issue of spatial resolution of measurements in general geomorphometry. This issue cannot be escaped : it will certainly affect Parsons' percentage of slope in the class -2 to +2° very heavily. Although the Gara matrix covered an area twenty times the size of the Netherhearth, the latter needed more profiles to estimate matrix-G summary statistics accurately (section 7.3), because of detailed relief picked up by the Netherhearth matrix at a resolution five times as detailed as that of the Gara. To illustrate this scale effect, figure 7.13 shows a set of profiles generated on a grid pattern of points of origin and traced with SLOPROFIL.2 using a version of the Netherhearth matrix thinned to a mesh size of 50 m . (It is important to note that the contours on this map were not derived from the matrix, and show detail that the latter at 50 m mesh clearly is not registering). These 14 profiles produce a statistic for mean gradient (in weighted analysis) of 5.39°, in excellent agreement with the 50 m matrix-G statistic of 5.32°. The dramatic change in scale of source matrix has not only decreased the number of profiles needed for adequate coverage of the topography, but has also increased mean profile length to 676.05 m . The profiles on figure 7.13 show that a matrix at 50m mesh of the Netherhearth generalizes out its minor talwegs, so that the catchment appears as a sloping tongue of land with a single linear concavity : the main valley of the Sike. This presents a different - and easier - sampling problem to that encountered with the Netherhearth matrix at 10 m mesh. It is clear that the scale of interest vitally affects sampling and results; more implications of choice of scale will be explored in the next chapter.

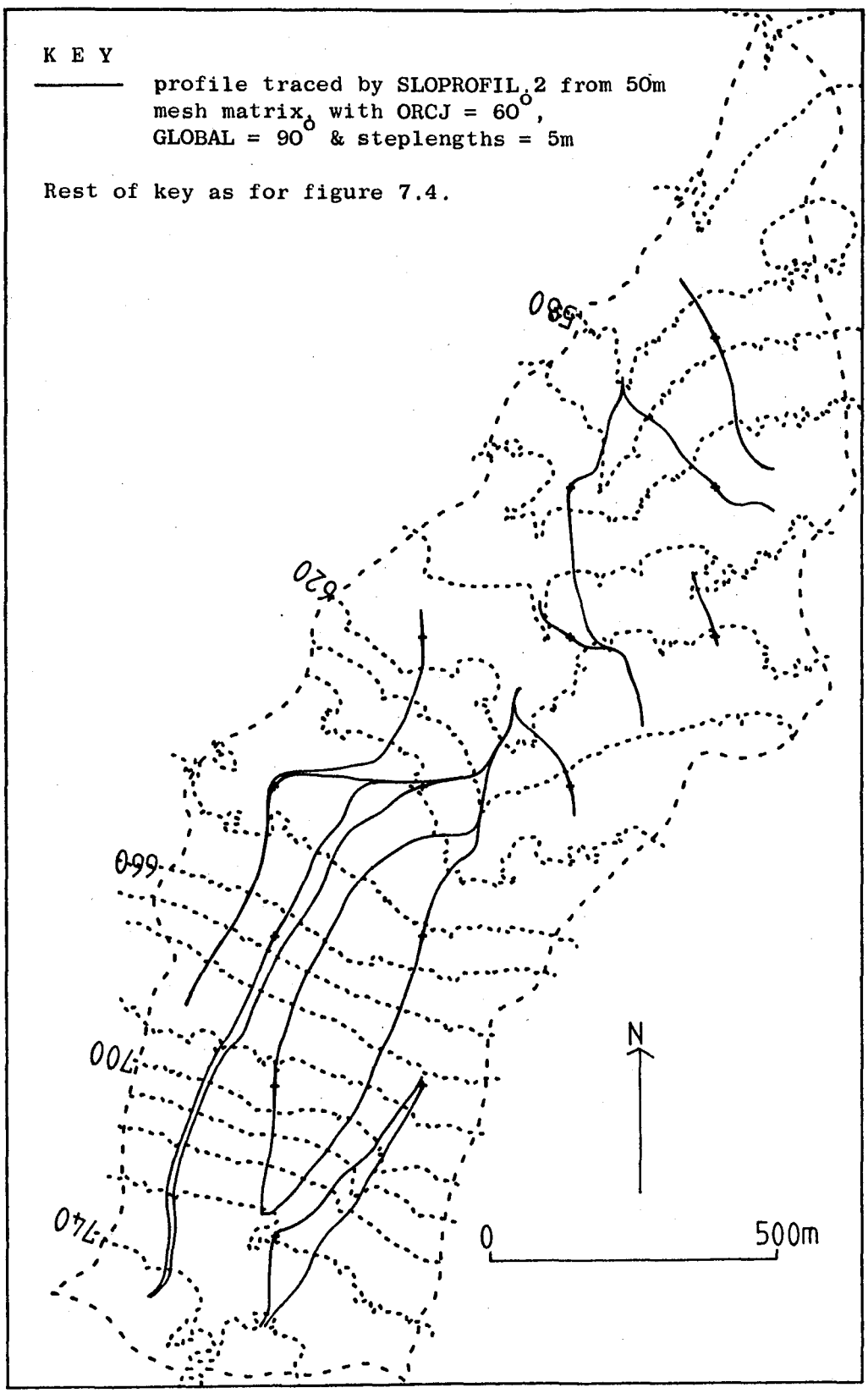


Figure 7.13 : Profiles located according to a grid pattern of points and traced using the Netherhearth matrix at a mesh size of 50 m.

CHAPTER 8 : THE ISSUES OF SCALE AND ACCURACY IN COMPUTER PROFILING

8.1 Introduction

8.2 Scale effects

i. Steplength used in matrix-based profiles

ii. Effect of grid mesh of source matrix

iii. Conclusions on scale effects

8.3 Comparison of surface approximation by G and by SLOPROFIL.2

8.4 Conclusions

8.5 Notation

8.1 Introduction

This chapter falls into two parts. In the first, various effects of scale in matrix-based profiles will be examined in more detail, as it has become clear from preceding chapters that several results obtained from these profiles vary with the horizontal constant lengths ('steplengths') used to trace them in SLOPROFIL.2, and with the mesh size of the source matrix used. The effects of these two types of scale change are quantified for derivatives of Gara and Netherhearth profiles; altitude statistics have been found to be resistant to scale effects, and are therefore not an object of this investigation.

In the second part of this chapter, the overall agreement between land form data from profiles generated by SLOPROFIL.2, and from matrices analysed with Evans' program G, are discussed. Differences in the way that SLOPROFIL.2 and G must model a landsurface are shown to have effects on results obtained by the two methods of measuring land form from matrices. It is vital that these effects be recognized and quantified, as they represent a limit to the degree to which a geomorphologist may expect results from SLOPROFIL.2 and from G to agree.

8.2 Scale effects

i. Steplength used in matrix-based profiles

The upper halves of tables 8.1 and 8.2 were made up in the following way. The source profile data are those obtained using 5 m steplengths with SLOPROFIL.2 working on the 50 m Gara and 10 m Netherhearth matrices, using in each case the terminating conditions found (in chapter 7) to give best agreement with G's altitude and gradient statistics. From this 5 m profile data, intermediate profile stations have been established by linear interpolation between the 5 m stations, such that the effects of using 3m, 7m, 10m and 50m (latter for Gara

Table 8.1 : Influence of scale on profiles generated in the Gara with ORCJ = 10° and GLOBAL = 40°

Profiles from 50m matrix with step-lengths =	Gradient in degrees						Profile curvature in degrees/100m						Mean profile length(m)
	mean	st.dev.	skew	kurt.	max.	min.	mean	st.dev.	skew	kurt.	max.	min.	
1) 3m	7.39	5.30	1.37	1.92	28.60	0.20	0.54	11.86	-1.32	4.88	34.86	-76.03	497.70
2) 5m	7.43	5.30	1.37	1.92	28.60	0.20	0.54	11.68	-1.30	4.56	31.31	-69.07	499.25
3) 7m	7.50	5.33	1.36	1.84	28.49	0.24	0.86	10.79	-1.03	3.23	30.97	-56.31	495.95
4) 10m	7.56	5.34	1.35	1.78	28.55	0.25	1.03	10.35	-1.14	4.03	29.41	-56.81	493.00
5) 50m	7.67	5.14	1.34	1.50	24.89	0.62	3.05	4.13	0.34	0.88	13.37	-11.35	470.00
6) 50m matrix with G	7.40	4.55	1.16	1.43	27.72	0.17	-0.02	9.62	-1.87	6.94	33.83	-74.97	
Profiles from 100m matrix with step-lengths =													
7) 3m	6.65	5.08	1.51	2.24	26.40	0.10	0.24	9.62	-1.61	6.66	27.06	-57.94	553.50
8) 5m	6.67	5.08	1.51	2.24	26.40	0.10	0.23	9.53	-1.58	6.08	24.33	-51.86	555.25
9) 7m	6.75	5.10	1.49	2.15	26.34	0.10	0.39	9.27	-1.61	6.39	23.69	-51.41	551.25
10) 10m	6.82	5.13	1.48	2.07	26.35	0.10	0.50	8.98	-1.62	6.66	22.74	-49.81	549.50
100m matrix with G	6.40	3.53	1.17	1.67	22.64	0.08	-0.02	5.91	-1.53	4.61	18.54	-39.19	

Note 1 : profile sets analysed with weighting applied such that each profile receives a weight of one.
Note 2 : figures closest to matrix-G's in each case are underlined

Table 8.2 : Influence of scale on profiles generated in the Netherhearth with ORCJ = 60° and GLOBAL = 90°

Profiles from 10m matrix with step-lengths =	Gradient in degrees						Profile curvature in degrees/100m						Mean profile length(m)
	mean	st.dev.	skew	kurt	max.	min.	mean	st.dev.	skew	kurt	max.	min.	
1) 3m	5.90	3.30	0.87	0.64	20.99	0.13	2.52	28.25	-0.47	2.58	113.75	-155.44	169.41
2) 5m	5.99	3.29	0.88	0.69	21.00	0.20	2.00	25.41	-0.42	1.74	110.30	-113.34	170.80
3) 7m	6.04	3.16	0.95	0.76	19.58	0.43	4.01	18.01	0.16	0.58	91.73	- 57.35	167.16
4) 10m	6.11	3.03	0.88	0.71	19.76	0.75	3.71	13.41	0.33	0.90	67.19	- 39.43	165.30
5) 10m matrix with G	5.95	3.10	0.64	0.94	23.90	0.00	0.17	28.32	-0.68	4.79	229.40	-286.04	
Profiles from 20m matrix with step-lengths =													
6) 3m	5.69	3.18	0.76	0.24	23.10	0.10	0.66	16.80	-0.08	3.01	92.47	- 77.90	329.52
7) 5m	5.72	3.17	0.78	0.29	23.10	0.10	0.43	15.91	-0.15	2.75	80.04	- 69.69	331.40
8) 7m	5.78	3.14	0.76	0.20	22.14	0.19	0.64	13.23	-0.21	2.75	68.32	- 58.71	327.60
9) 10m	5.79	3.12	0.76	0.26	22.06	0.25	0.92	10.88	0.09	2.47	56.48	- 57.35	324.40
10) 20m matrix with G	5.62	2.65	0.49	-0.16	16.00	0.02	0.28	13.31	-1.01	7.17	65.95	-128.06	

See notes 1 and 2 on table 8.1

only) steplengths on the same profiles may be investigated.

Looking first at the Gara statistics (table 8.1), it is apparent that mean gradient (column 1) increases slightly with increasing steplength. The total difference in this statistic of 0.28° between the steplength = 3m profiles and the steplength = 50 m profiles, is less than the increase in mean gradient for profiles (with steplength = 5m) traced with terminating variable GLOBAL at 40°, and at 30° (table 7.2). The slightly shorter total length of profiles with longer steplengths (see right-hand column, table 8.1) may have helped to raise the mean gradient figure for them, because the algorithm that interpolated the different steplengths from the 5 m profile data, started at the crest of a slope and so the left-over segment of profile at the end would be towards the talweg and therefore likely to be of lower gradient. However it is clear that some of the difference in this statistic for different steplengths must be a direct consequence of steplength size itself. This effect on gradient statistics is only slight however : standard deviation of gradient hardly changes over a steplength increase from 3 to 10 m, and decreases somewhat in the 50m case although it never reaches the matrix-G value (row 6, table 8.1). Thornes (1973) has found that standard deviation of field slope angles is influenced by the ground surface length used. Skewness, maximum and minimum of gradient show considerable stability over the range in steplength from 3 m to 50 m. This is remarkable when one remembers that in the latter case the land between two profile stations 50 m apart is being generalized to a straight line.

For profile curvature (upper right-hand side of table 8.1), a contrasting situation is seen. The central tendency of this attribute is relatively steady at near zero, but standard deviation of profile curvature is sensitive to steplength. In theory one might expect

profile curvature data from use of 1 m steplengths to be most like G's figure, which is obtained as a derivative calculated over 1 m and multiplied by 100 to be expressed in degrees per 100 m. Since it would have created artificiality in the results to interpolate 1 m steplength profiles from 5 m steplength data, a separate run of SLOPROFIL.2 was performed on the 50 m matrix of the Gara with 1 m steplengths. These results are not presented in table 8.1 because they are not comparable with the others, as profiles came out longer using the smaller steplength despite use of the same terminating conditions and profile points of origin. (This is because shorter steplengths allow a profile to negotiate a change in slope more gradually and so avoid triggering termination due particularly to ORCJ. Figure 8.1 confirms that profiles traced with different steplengths follow the same paths in a catchment however.) The standard deviation of profile curvature obtained in that instance was 11.78°/100 m, similar to the 3m-steplength statistic reproduced in table 8.1, and some way off matrix-G's figure. Profile curvature is much more sensitive to steplength than is gradient : over the change in steplength from 3 to 50 m its standard deviation decreases by an amount more than an order of magnitude greater than the decrease in standard deviation of gradient over the same steplength change.

Turning to the upper half of table 8.2, for profiles traced in the Netherhearth catchment at 10 m mesh, it can be seen again (column 1) that mean gradient varies with steplength. Again the magnitude of variation achieved by steplength alteration, at 0.21°, is only comparable to the effect of a small change in terminating conditions, from ORCJ = 50° to ORCJ = 40° (table 7.3). Standard deviation of gradient is also observed to vary with steplength, and agreement with G is attained with 7 m steplengths. Skewness, kurtosis, maximum and minimum of gradient are fairly stable over the range in

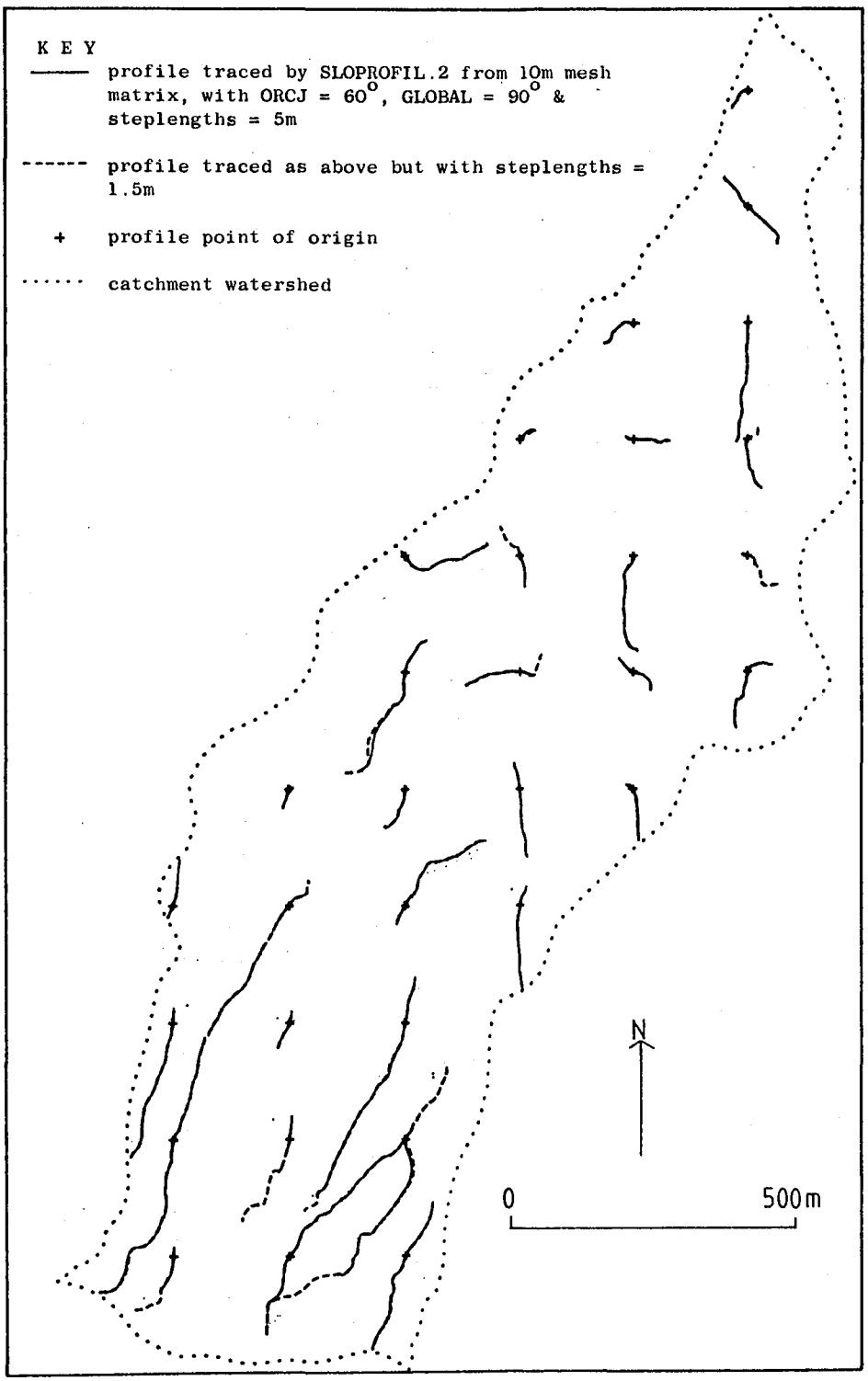


Figure 8.1 : Profiles traced with different steplengths by SLOPROFIL.2, from the same points of origin in the Netherhearth catchment.

steplength size, although 10 m steplengths pull in the tails of the gradient distribution somewhat compared with 3 m steplengths, as did 50 m steplengths in the Gara (in both cases this large steplength is equal to the mesh size of the matrix).

For profile curvature in the Netherhearth (upper right-hand side of table 8.2), the situation is again different from the Gara's on account of the more detailed mesh of the Netherhearth matrix. Standard deviation of profile curvature is best estimated by profiles with 3 m steplengths, although the tails of this distribution are much shorter than those of the matrix with G.

8.2 ii Effect of grid mesh of source matrix

It is interesting first of all to compare visually profiles generated from different matrix mesh sizes. Figure 8.2 shows matrix-based profiles in the Gara catchment traced with 5 m steplengths from the altitude matrix at 50 m mesh and from that matrix thinned to 100 m mesh (profiles in pecked lines on figure). Agreement between the two sets is shown to be least good for areas of low-angled divide where there is a less consistent signal from matrix altitudes (e.g. profile 17, figure 8.2), and best for relatively steep valleyside slopes (e.g. profile 11). Profile 8 illustrates how a slightly curved orthogonal generated from 50 m data is generalized to a straighter course when the 100 m source matrix is used.

The overall agreement is good, indicating that correct identification of the path of contour orthogonals is resistant to the effects of a decrease in matrix mesh size from 50 to 100 m. It has also been shown that 50 m matrix profiles agree well with field profile paths (chapter 5). Figure 8.2 shows that not only profile paths, but also termination places agree to a large extent for the two profile sets. Profile 10 is a notable exception, as its point of origin falls on a

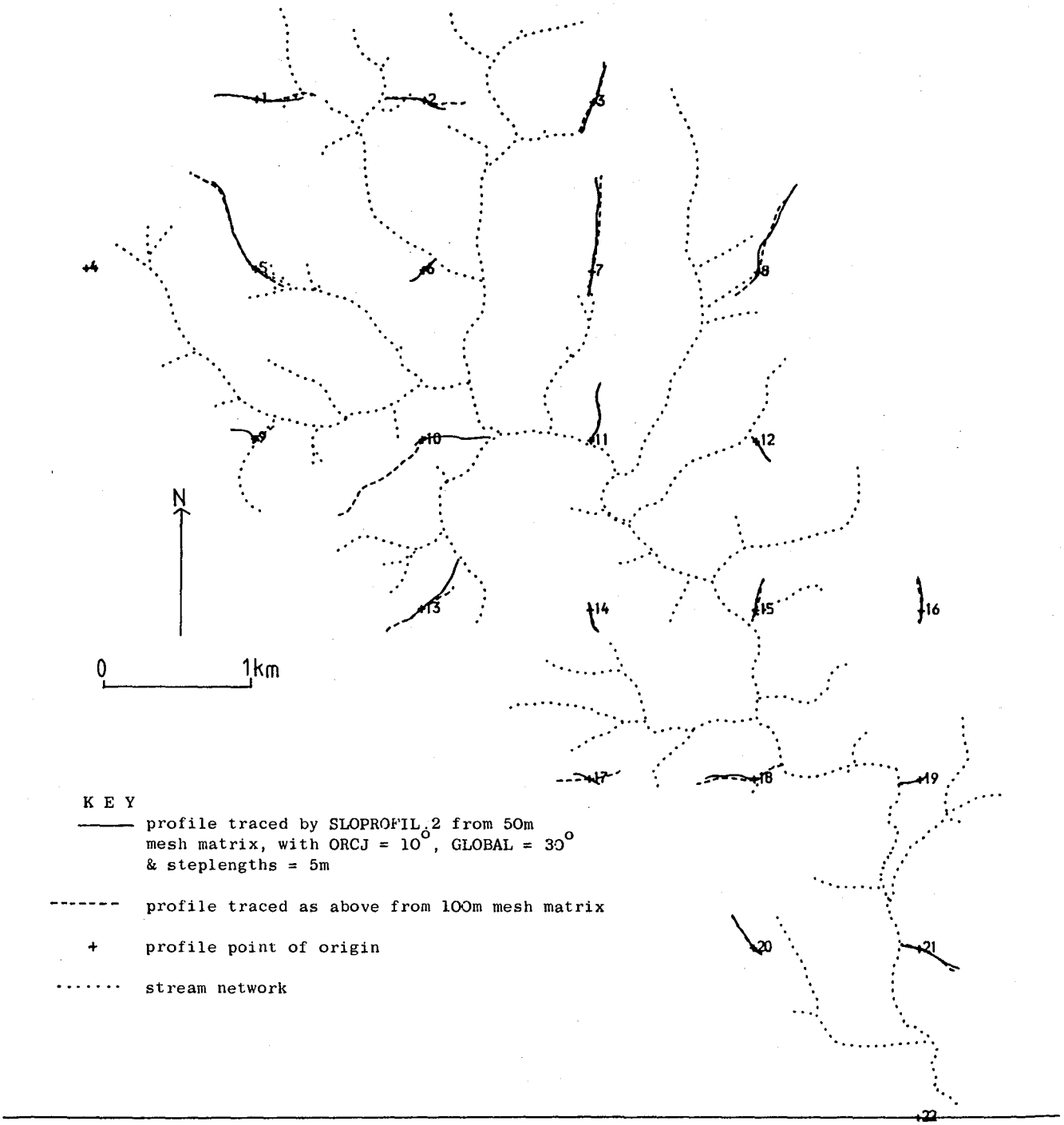


Figure 8.2 : Profiles traced from the same points of origin by SLOPROFIL.2 from the Gara matrix at 50 m and at 100 m mesh.

local summit which is recognized by the profile from the 50 m matrix but generalized out by the 100 m data. In this case the latter gives a ridge profile rather than a slope profile.

The profiles in pecked lines on figure 8.3 were generated from the same points of origin again, but using the source matrix at 150 m mesh. Identification of contour orthogonals is noticeably less accurate in this case : a profile with starting-location near a talweg was particularly vulnerable, as can be seen from profile 11 which ascended the opposite slope in the 150 m run, and profile 18 which ignored the neighbouring hillslope and followed the talweg. The general tendency of these coarse-mesh profiles to follow divides and talwegs rather than hillslopes is an important disadvantage of using a matrix as coarse as 150 m in this topography. This effect was also present to a lesser extent in the 100 m mesh sample, where profile 10 followed a divide as was observed above. Relief features that are sustained over long distances inevitably control the paths of the coarse-mesh orthogonals, and these features are the talwegs and divides rather than the hillslopes that are the desired objects of study.

Turning to statistical comparisons, the lower halves of tables 8.1 and 8.2 display statistics from profiles generated from the Gara and Netherhearth matrices thinned once (to 100m and 20m respectively). 5 m steplength profiles were traced by SLOPROFIL.2 across these thinned matrices, from the same pattern of points of origin and according to the same terminating conditions as were used for the upper halves of the two tables discussed in the previous sub-section. 3m, 7m and 10m steplengths were interpolated from the profile data as before.

The right-hand column of table 8.1 shows that the 100 m Gara matrix produces profiles about 50 m longer on average than those from the 50 m matrix with the same terminating conditions. From what was

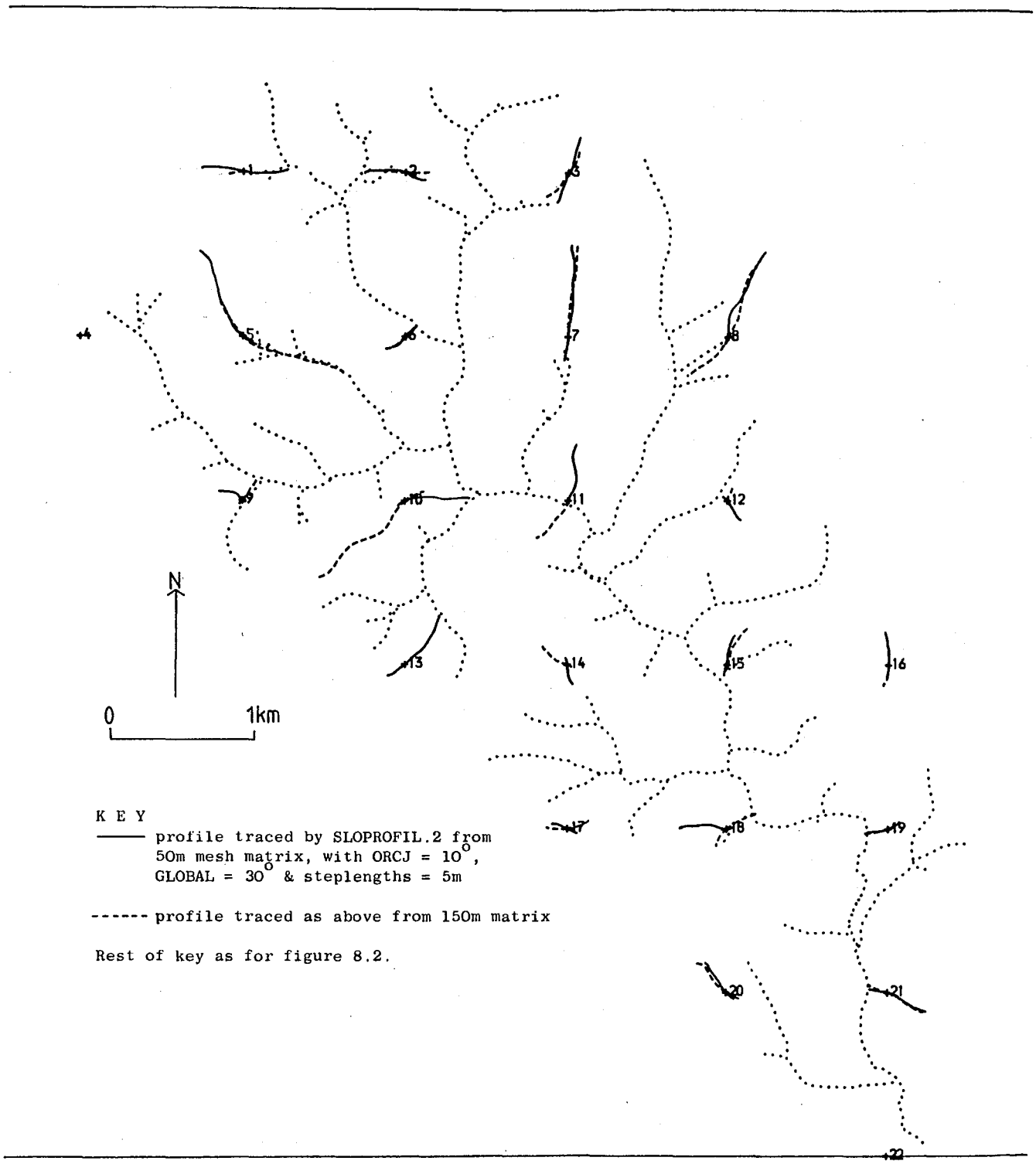


Figure 8.3 : Profiles traced from the same points of origin by SLOPROFIL.2 from the Gara matrix at 50 m and 150 m mesh.

found out about the influence of profile length on Gara summary statistics in the previous two chapters, one would expect the longer 100 m matrix-based profiles to underestimate G's mean gradient compared with the shorter 50 m matrix-based profiles, because long profiles in this catchment tend to incorporate more low-angled crest and talweg slope. However, the 100 m matrix-based profile mean gradient figures are greater than matrix-G's with a 100 m mesh (row 11, table 8.1) for all the steplengths investigated.

It is not very encouraging for a fieldworker wanting to know how long a slope to survey, to find that matrices of an area at different mesh sizes give different answers. However investigations in chapters 5 and 6 established a fairly good statistical consistency between field-measured profiles and their 50 m matrix-based counterparts in the Gara catchment. It must be the case that a matrix at 100 m mesh produces a topography sufficiently different from that at 50 m mesh to present a new sampling problem. Experience with different catchments and different mesh sizes of matrix will enable geomorphologists to gauge the range of matrix mesh sizes they can use for reliable field comparison. Complete coverage of Great Britain by Ordnance Survey maps of at least 1:10,000 or 1:10,560 scale enables an investigator to make a matrix at least as detailed as 50 m mesh anywhere in this country, and this study has shown this to be adequate for field comparison in the Gara.

Doubling of the matrix mesh size produces a much greater effect on profile mean gradient than a change in profile steplength. However standard deviation of gradient from matrix-based profiles is comparatively little altered by the mesh change, although from G it decreases from 4.55 to 3.53°. The maximum gradient from G also is more reduced by the change from 50 to 100 m mesh (from 27.7 to 22.6°) than is the maximum gradient from computer profiles for the same mesh change

(e.g. for 3 m steplength profiles, reduction is from 28.6 to 26.4°). The gradient distributions of 50 m profiles had tails much more similar to matrix-G's at 50 m mesh; the change to 100 m mesh has caused profiles and G to diverge in this respect, so that 100 m profiles over-estimate G's skewness of gradient more than did 50 m profiles. If a geomorphologist did want to apply the approach of this thesis with only a coarse-mesh matrix to hand, transformation of matrix-G and profile-derived attributes would be advisable to harmonize the shapes of their distributions so that central tendency and spread could be reliably compared.

For profile curvature (lower right-hand part of table 8.1), a similar situation is seen, the majority of profile statistics having declined from their 50 m matrix values, but not by as much as is the case for matrix-G statistics over the mesh change. A step-length considerably greater than 10 m would be required to pull in the tails of the distribution as far as those of the 100 m matrix with G. Standard deviation of profile curvature exceeds the matrix-G figure by 52% for 10 m steplength, which must be partly a result of these long tails. Skewness, however, is more comparable, and more stable over different steplengths, at 100 m mesh.

For the Netherhearth, the effect of doubling matrix mesh size is less marked, as the increase involved is from 10 to 20 m rather than 50 to 100 m. Again as in the Gara, profiles came out longer for the same terminating conditions on the less detailed matrix. The 20 m matrix-based profile gradients are longer-tailed and more skewed than the G distribution, a similar problem to that described for the Gara at 100 m mesh.

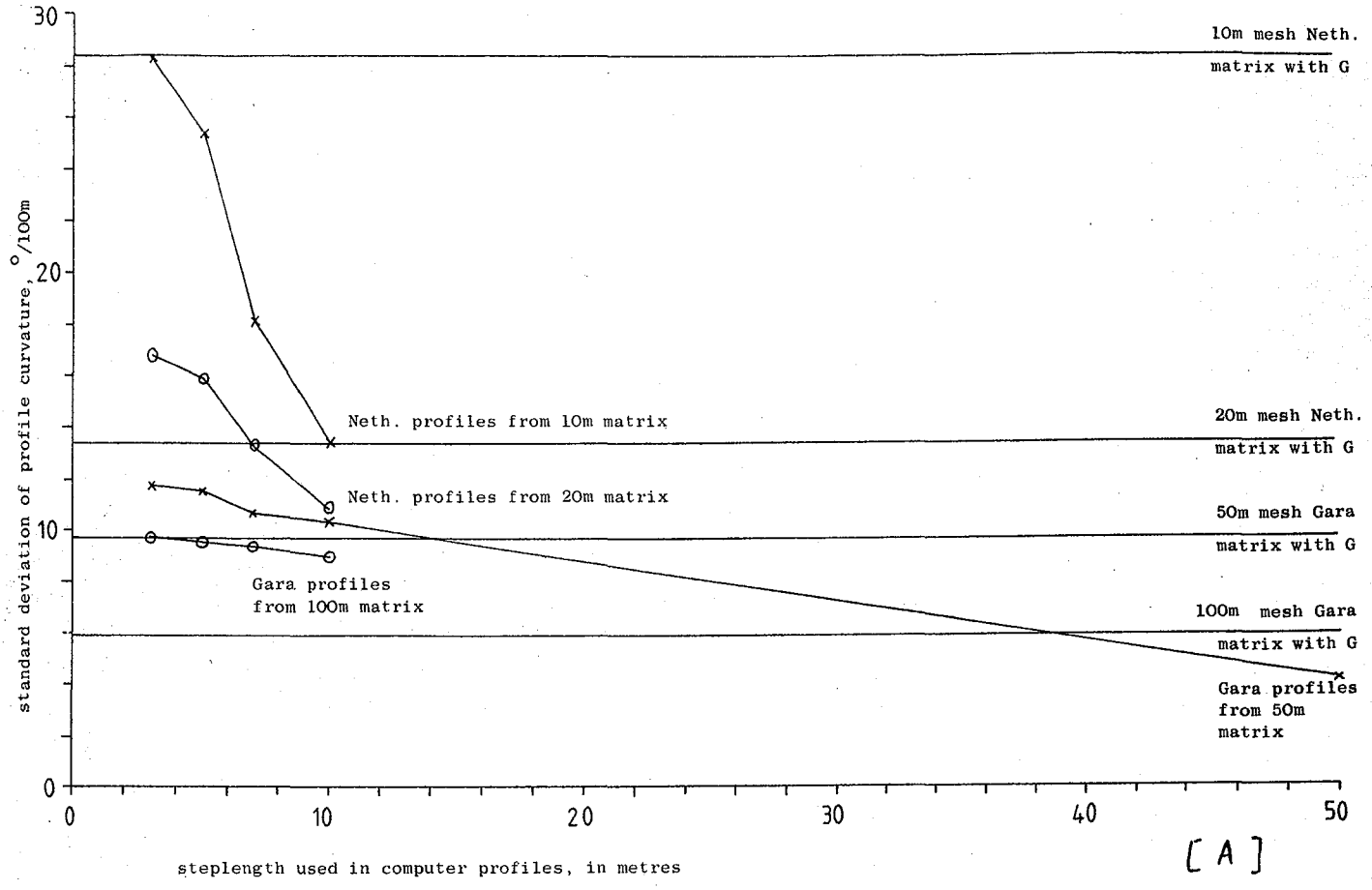
8.2 iii Conclusions on scale effects

Figure 8.4 sums up the relative effects of the two types of scale change to which attributes of computer profiles are sensitive : steplength size and matrix mesh size. The figure shows the situation for standard deviation of profile curvature, the most sensitive to scale of the moment-based summary statistics of land form attributes.

It is clear from figure 8.4 (A) that a lower estimate of this parameter can be obtained either by increasing steplength, or by increasing matrix mesh spacing. It is also clear that at more detailed matrix meshes (10 m Netherhearth), changing profile steplength has a greater effect than when mesh size is larger (20 m Netherhearth), because the matrix is picking up less detailed-scale variability at the latter scale.

For detailed matrix meshes (10 m), profile curvature must be generated over small steplengths (3 m) to be comparable with G's; for a larger matrix mesh (50 m), steplengths of about 14 m will give agreement with G. In both cases this involves using a steplength just under one-third the size of the matrix mesh, as is demonstrated in the dimensionless plot, figure 8.4 (B). If comparability with matrix-G profile curvature statistics is sought from computer profiles, steplengths of this size must be used.

On the other hand it is not clear why profile curvature estimated from 1 m steplengths is not comparable with G's, calculated in all cases as a second derivative over 1 m. One answer to this question may lie in differences due to the different land surface models used by G and SLOPROFIL.2, the subject of the next section. However one remaining scale contrast between G and SLOPROFIL.2 first needs to be investigated on its own : that due to the different intensity (spacing) of sampling locations when, for example, Gara profiles with 5 m steplengths are being compared with matrix-G results from sampling points 50 m apart.



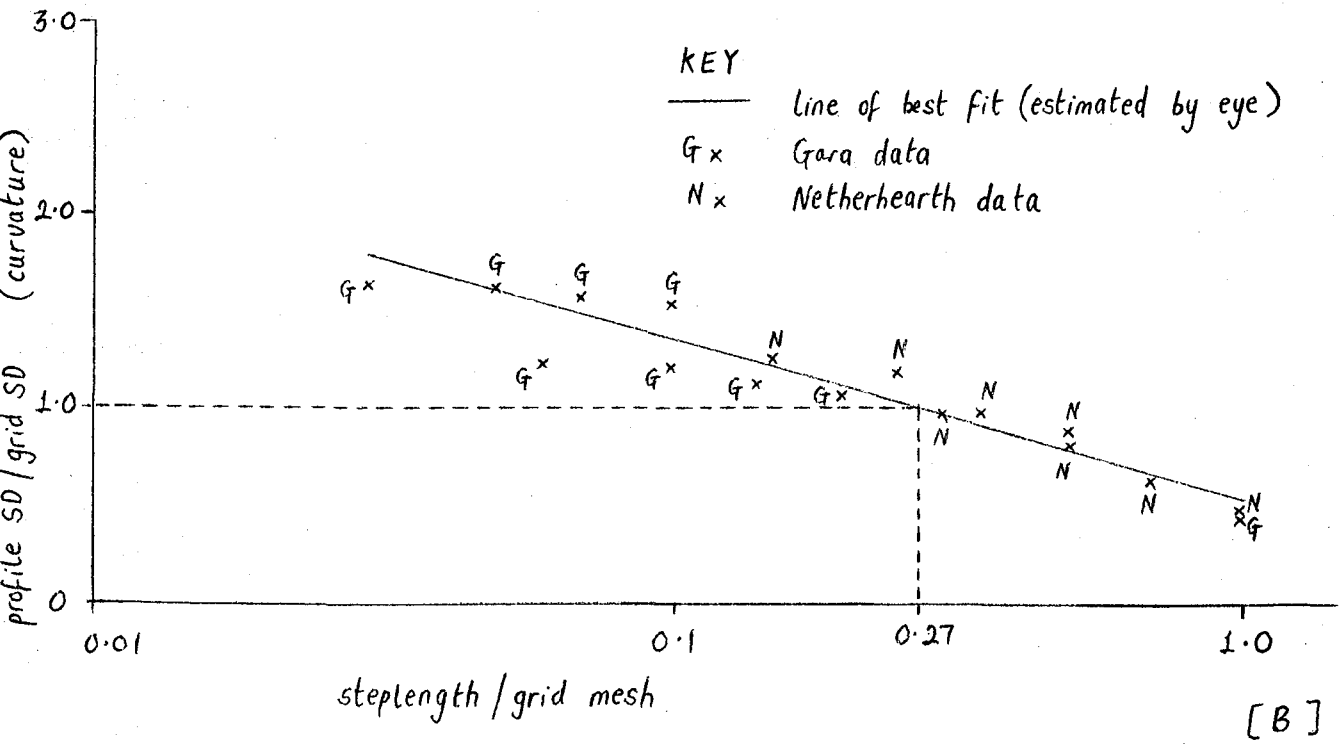


Figure 8.4 : Variation of standard deviation of profile curvature with profile steplength and matrix mesh size in Gara and Netherhearth.

To do this, the successful matrix-based Gara profile sample(with ORCJ = 10°, GLOBAL = 40°, for matrix mesh size = 50 m and steplength = 5m) and Netherhearth profile sample(with ORCJ = 60°, GLOBAL = 90°, for matrix mesh size = 10 m and steplength = 5m) were taken and instead of sampling every steplength in weighted analysis, only steplengths at intervals equal to the matrix mesh size were included. Thus in the case of the Netherhearth, profile steplengths equal to 5 m necessitated a sampling of every second steplength to achieve the 10 m interval of the matrix with G. For the Gara, every 10th steplength was included, to make the sampling interval like the 50 m matrix with G. Results of this less intense sampling by profiles are presented in table 8.3, with the complete profile sample results for comparison.

It is clear from table 8.3 that some statistics are altered by the decrease in sampling intensity. Profile curvature statistics appear to be the more unstable : the extremes of the distributions of this attribute are much altered in both Gara and Netherhearth cases. Gradient is more robust, although a slight decrease in mean gradient is seen in both cases. It is evident that the disagreements between SLOPROFIL.2 and G cannot be explained solely by differences in land surface sampling intensity between the two programs : in both Gara and Netherhearth cases, the reduced intensity of profile sampling still over-estimated G's standard deviation of gradient, and for the Gara standard deviation of profile curvature continued to be over-estimated as well.

Table 8.3 : Effect of sampling computer profile steplengths at intensities similar to G's sampling of the matrix

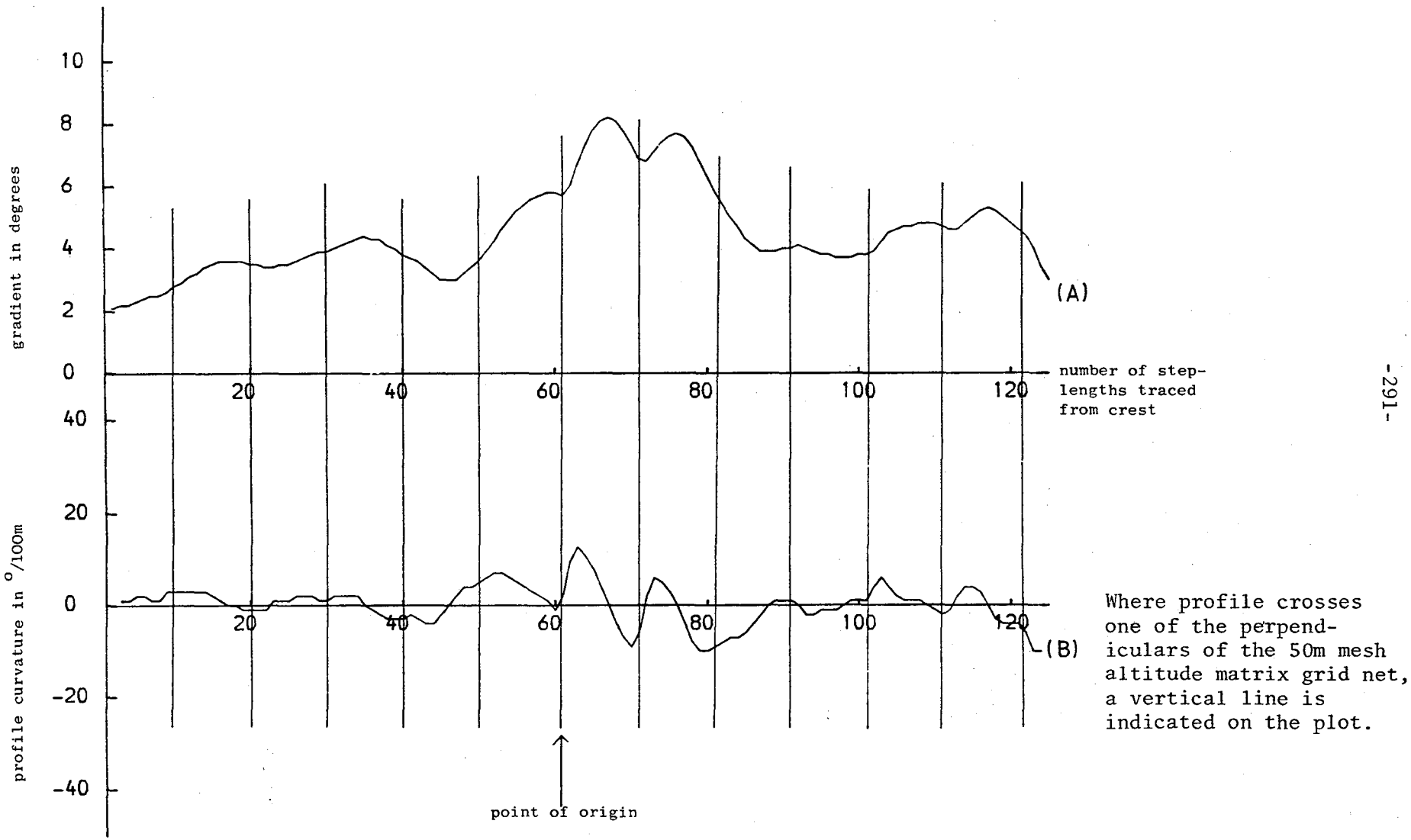
	Gradient in degrees						Profile curvature in degrees/100 m					
	mean	st.dev.	skew	kurt	max.	min.	mean	st.dev.	skew	kurt.	max.	min.
Gara profiles, analysing every 5m steplength	7.43	5.30	1.37	1.92	28.60	0.20	0.54	11.68	-1.30	4.56	31.31	-69.07
Gara profiles, analysing every 10th 5m steplength	7.16	5.38	1.39	2.07	28.60	0.70	1.04	10.37	-1.05	2.47	20.95	-37.99
Netherhearth profiles, analysing every 5m steplength	5.99	3.29	0.88	0.69	21.00	0.20	2.00	25.41	-0.42	1.74	110.30	-113.34
Netherhearth profiles, analysing every 2nd 5m steplength	5.91	3.34	0.88	0.69	18.50	0.20	3.51	23.67	0.15	0.81	99.90	-65.35

8.3 Comparison of surface approximation by G and by SLOPROFIL.2

In the previous section it was made clear that SLOPROFIL.2 has a tendency to over-estimate standard deviation of the surface derivatives gradient and profile curvature by comparison with G. An inescapable conclusion of this observation is that SLOPROFIL.2 sampling within squares defined by four altitude matrix vertices, is picking up some variation in modelled land surface which is not apparent to G, sampling only at vertices. To investigate this, the variation of gradient and profile curvature along profiles were plotted; the result is shown for a Gara profile in figure 8.5. The vertical lines on figure 8.5 indicate the places where the profile line crosses one of the lines in the X or Y direction that make up the altitude matrix grid. The relevant part of the Gara grid, with profile path marked on, is shown in figure 8.6.

The gradient plot of figure 8.5 shows that there is a tendency for gradient to increase or decrease within a square, compared with its value along the square's margins. This effect is particularly marked where gradient is high, between steplength number 60 and number 80 on the figure. Since second derivatives were not calculated in SLOPROFIL.2 for reasons given in chapter 4, the profile curvature values were calculated from the succession of gradients along a profile line afterwards, and therefore by definition follow the trends exhibited by gradient, as plot (B) of figure 8.5 shows. Profile curvature is at its highest positive and negative peaks between steplengths 60 and 80 where gradient increases most within the squares.

Figure 8.7 (A) shows altitude variation for the same profile from crest to base : the traditional profile plot used by geomorphologists. No irregularities are visible here. It is evident that only derivative values are prone to bulge within squares.



Where profile crosses one of the perpendiculars of the 50m mesh altitude matrix grid net, a vertical line is indicated on the plot.

Figure 8.5 : Plots showing variation of (A) gradient and (B) profile curvature from crest to base of Gara profile 1 in figure 8.2.

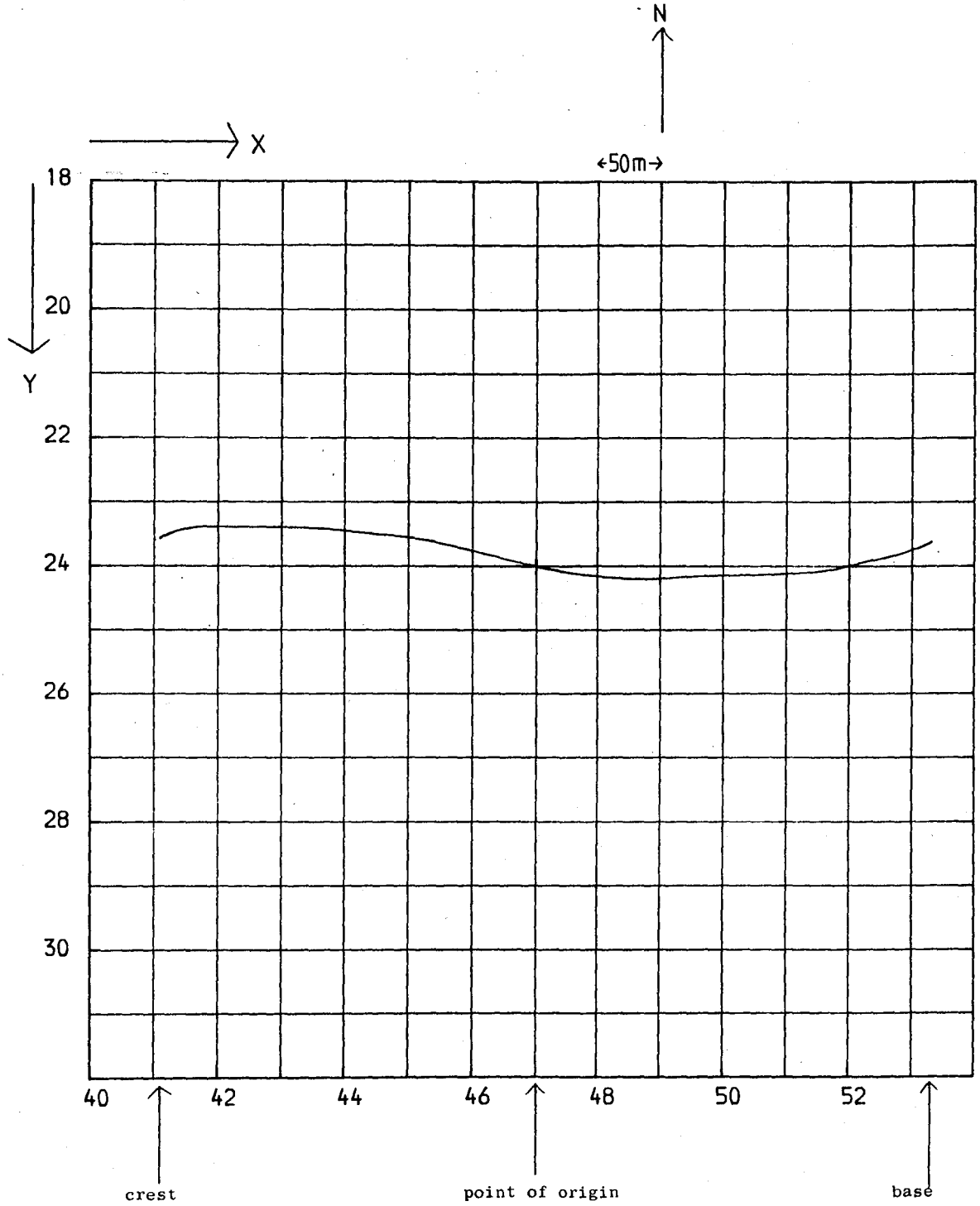


Figure 8.6 : Map of path of profile whose derivatives are plotted in figure 8.5, across Gara's grid mesh.

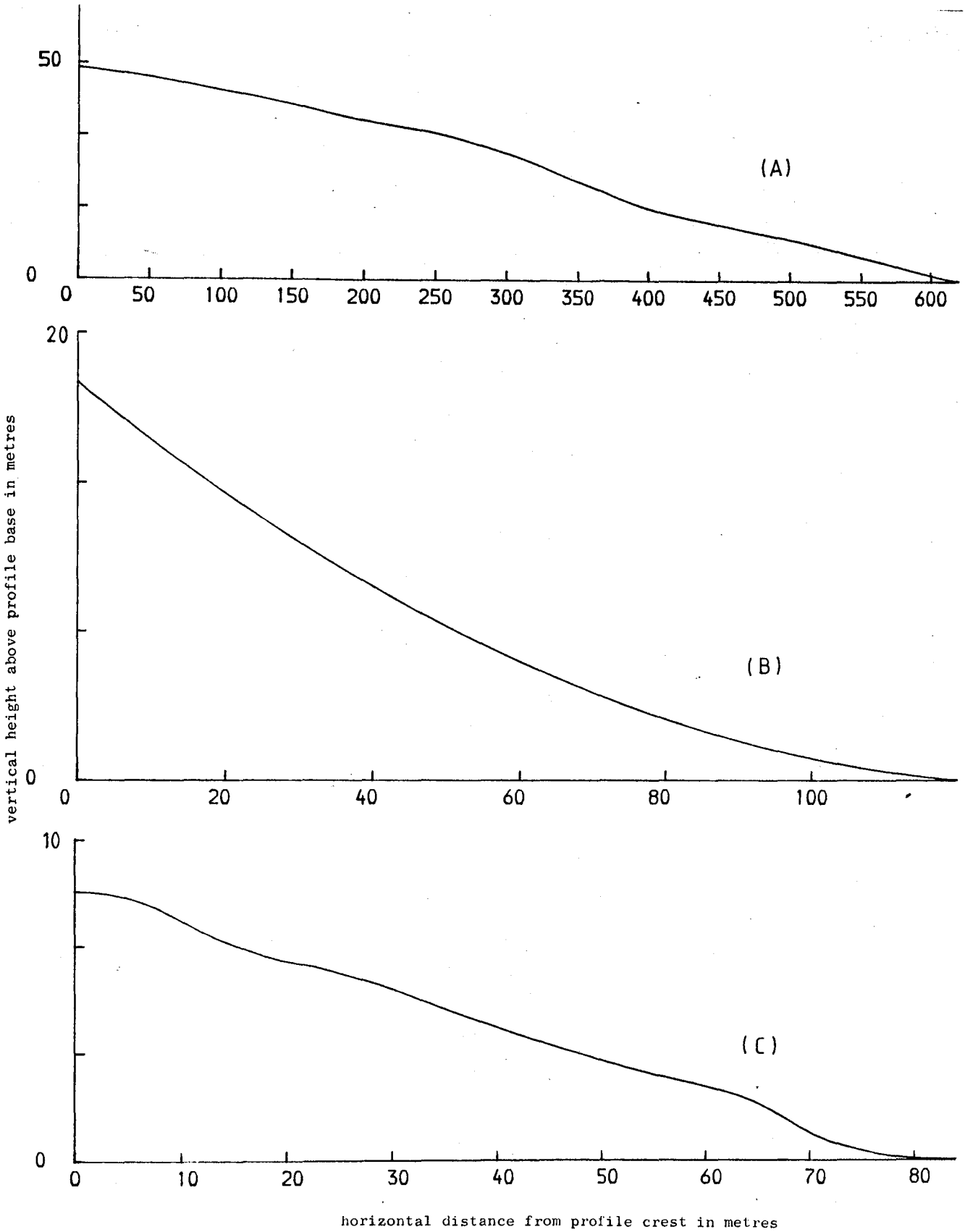


Figure 8.7 : Profile plots at 3X vertical exaggeration for

(A) the Gara profile

(B) the parabola

(C) the Netherhearth profile

If this irregularity in derivative values were due to a programming error in SLOPROFIL.2, for example an error in multiplying out the long equations necessary to apply Jancaitis and Junkins' weighting function to the four quadratics that overlap in every square, then one would expect the effect to be manifested whatever surface one were tracing a profile across. To test this, altitude matrices were generated according to two mathematical functions. The first was a plane; the second was Troeh's (1964, 1965) paraboloid of revolution, having the equation :

$$Z = 0.001X^2 + 0.001Y^2$$

The paraboloid profile is shown in figure 8.7 (B), and its gradient and profile curvature plotted against distance from the crest of the profile in figure 8.8. The latter figure shows decisively that the program SLOPROFIL.2 is not distorting the surface : the parabola's constantly decreasing gradient and constant profile curvature are perfectly represented by the output from SLOPROFIL.2, despite the trace crossing several matrix squares (figure 8.9). Results from the plane were again as they should be (constant gradient, no curvature).

In the case of the parabola or plane, the four quadratics centred on the corners of each final square to which the Jancaitis and Junkins weighting function is applied, are all a perfect fit to a surface whose equation does not vary over the entire length of the profile. To give an example, a final square in the parabola run with SLOPROFIL.2 had the following quadratics centred at its corners (as depicted in figure 4.5):

(centred upper L.H. vertex)

$$Z = 0.001X^2 + 0.001Y^2 + 0.1X + 0.1Y + 5.0 \qquad (1)$$

(centred upper R.H. vertex)

$$Z = 0.001X^2 + 0.001Y^2 + 0.11X + 0.1Y + 5.525 \qquad (2)$$

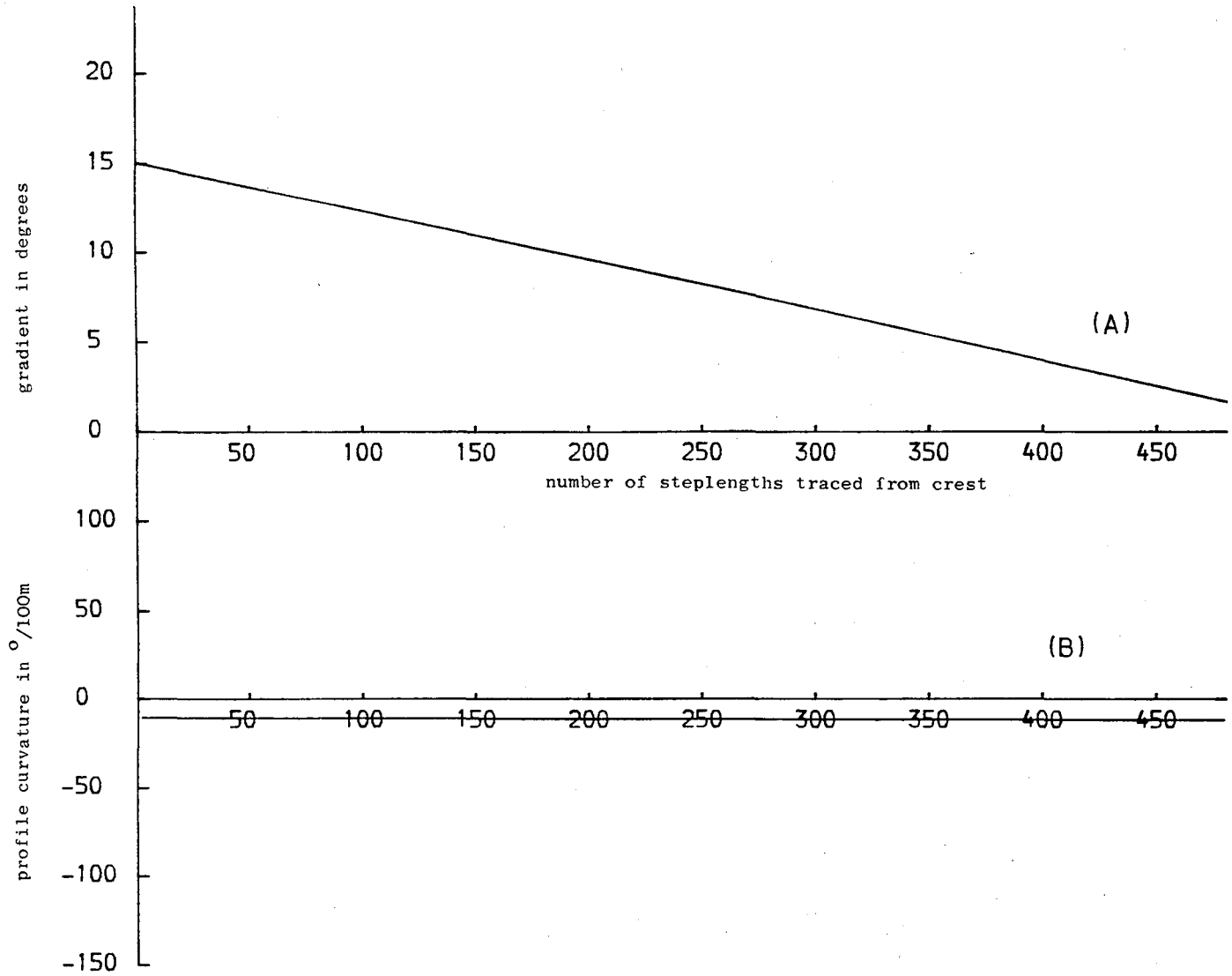


Figure 8.8 : Plots showing variation of (A) gradient and (B) profile curvature from crest to base of the parabola.
(Profile data generated by SLOPROFIL.2.)

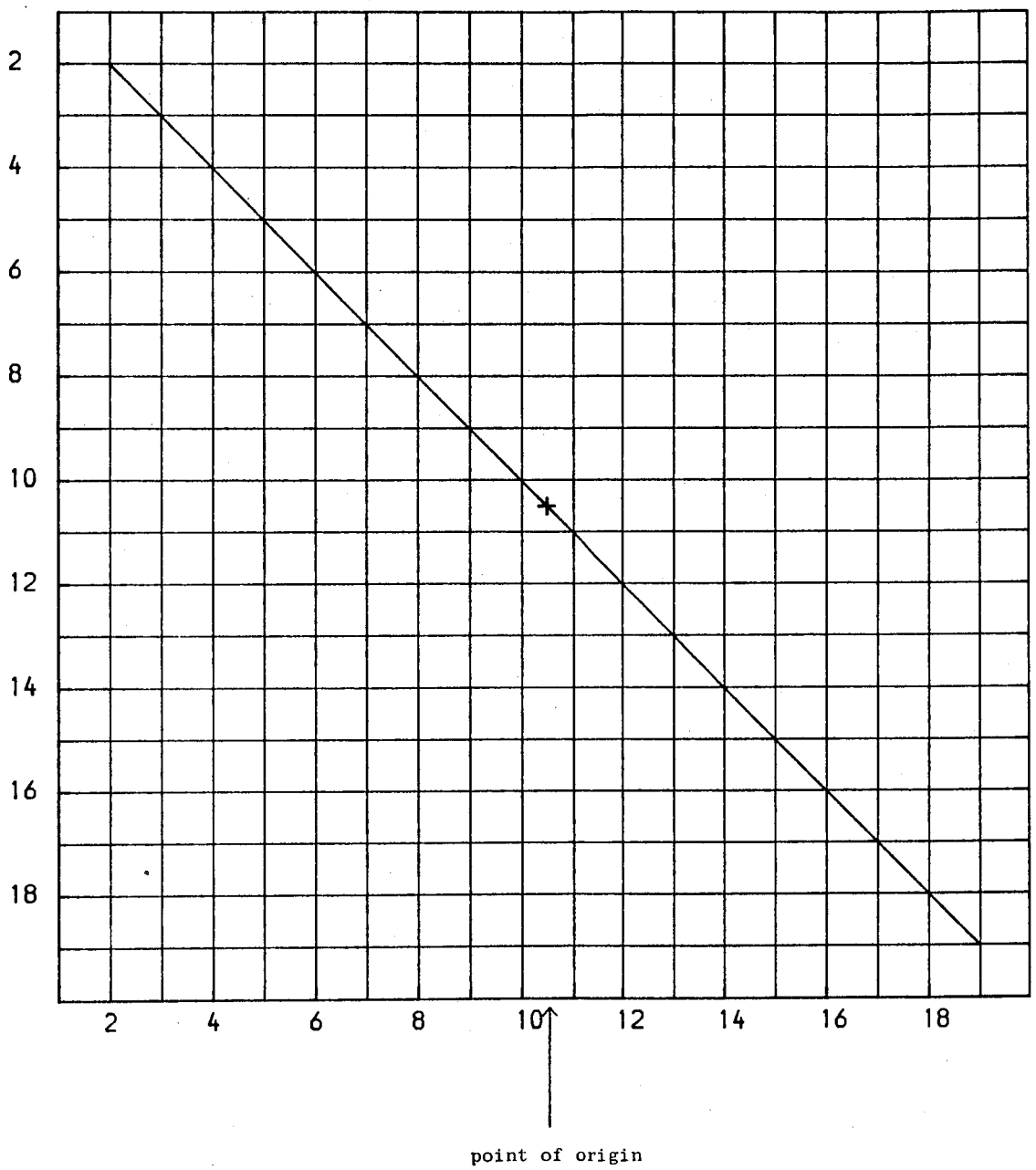


Figure 8..9 : Map of path of parabola across grid mesh of the 'paraboloid of revolution' surface.

(centred lower L.H. vertex)

$$Z = 0.001X^2 + 0.001Y^2 + 0.1X + 0.11Y + 5.525 \quad (3)$$

(centred lower R.H. vertex)

$$Z = 0.001X^2 + 0.001Y^2 + 0.11X + 0.11Y + 6.05 \quad (4)$$

It can be verified that these are simply translations of the same equation due to the origins of the four quadratics being at different locations. The height at the centre of the final square, grid mesh = 5m, is found by substituting

$X = 2.5$, $Y = 2.5$ into equation 1,

$X = -2.5$, $Y = 2.5$ into equation 2,

$X = 2.5$, $Y = -2.5$ into equation 3, and

$X = -2.5$, $Y = -2.5$ into equation 4,

giving a height of 5.5125 m in each case. The estimation of profile curvature at this same location by the four quadratics is found by applying to each the following formula (derived from the standard two-dimensional expression for curvature given in Young, 1978, 3) :

$$\text{profc} = \frac{-2(a\cos^2\theta + b\sin^2\theta + c\sin\theta\cos\theta)}{\{1 + (2r(a\cos^2\theta + b\sin^2\theta + c\sin\theta\cos\theta) + d\cos\theta + e\sin\theta)^2\}^{3/2}}$$

where

a,b,c,d, and e are coefficients of the quadratic equation in X and Y (see chapter 4);

θ is the angle made between a line joining the centre of the final square to the centroid of the quadratic, and the line $y = 0$ for that quadratic (analogous to the situation depicted in figure 4.7);

r is the length of the line joining the centre of the final square to the centroid of the quadratic (cf. figure 4.7).

(This equation is multiplied by $100 \times 180/\pi$ to give a result in degrees per 100m). Each of the four quadratics set out above yields the same estimate of profile curvature, of -11 °/100 m, at this point.

By contrast, for real terrain, the quadratic centred on each corner of a final square is likely to be only a least squares fit to the 3 x 3 altitudes to which it was fitted, and the four quadratics overlapping in the final square are unlikely to be the same, as was the case with the parabola. Even in the unusual situation that a hillslope did describe a perfect mathematical function in three dimensions (such as a paraboloid of revolution), at some point the crest of that hillslope would be encountered and the function required to describe the surface would change. Thus in real terrain SLOPROFIL.2 must usually have to average four different quadratics within the area of a final square, and the similarity of the outcome with G (sampling only at the vertices) is likely to depend on how similar the four quadratics covering a final square are to each other. Below are listed a set of four quadratics for a Gara 50 m mesh square. The upper left-hand corner vertex of this square was the starting-point of the profile whose attribute plots are depicted in figure 8.5. The quadratics are :

(centred upper L.H. vertex)

$$Z = -0.000366X^2 + 0.000366Y^2 - 0.000183XY - 0.095504X - 0.022352Y + 159.715186 \quad (1)$$

(centred upper R.H. vertex)

$$Z = -0.000041X^2 + 0.000813Y^2 + 0.000061XY - 0.115824X - 0.024384Y + 153.280520 \quad (2)$$

(centred lower L.H. vertex)

$$Z = -0.000325X^2 + 0.000284Y^2 + 0.000549XY - 0.093472X + 0.010160Y + 159.444253 \quad (3)$$

(centred lower R.H. vertex)

$$Z = 0.000081X^2 + 0.000325Y^2 + 0.000549XY - 0.105664X + 0.032512Y + 153.890120 \quad (4)$$

The heights at the central point of the square come out at

156.654 m	by substitution into equation	1
156.011 m	"	2
156.485 m	"	3, and
156.316 m	"	4

This represents agreement to within 0.65 m. But the estimations of curvature at the central point by the four cover a wider percentage of dispersion, being estimated at 1, -4, 3 and -5°/100 m respectively by quadratics 1,2,3 and 4 (applying the curvature equation set out above), a range in estimates of 8°/100 m. Thus as the profile proceeds from the point of origin towards the east, across the top of this JNJ-fitted square (as the trace in figure 8.6 shows), it is predominantly controlled first by the positive curvature of quadratic 1, and then by the negative curvature of quadratic 2, as can be seen on the plot of profile curvature, figure 8.5 (B). The fact that these neighbouring quadratics disagree in their estimations of curvature leads to irregularity in the derivatives of a profile that must pass from the domain mainly controlled by one quadratic in the weighted average square, to that controlled by another.

Figure 8.10 shows that the tendency to dispersion of derivative values inside a final square is also present in some parts of the Netherhearth catchment; the profile depicted in figure 8.10 followed the trace indicated in figure 8.11. Its altitude was again a more reasonable plot, shown in figure 8.7(C). Looking in more detail at one of the squares which produced a noticeable bulge in the gradient plot of figure 8.10 (the second square from the crest), the estimations of altitude at its centre by the quadratics at its four corners were 603.138 m, 602.752 m, 603.345 m and 603.158 m. The disagreement is to within 0.60 m, which is slightly smaller than the height disagreement for the Gara square investigated above, but it should be remembered

Where profile crosses one of the perpendiculars of the 10m mesh altitude matrix grid net, a vertical line is indicated on the plot

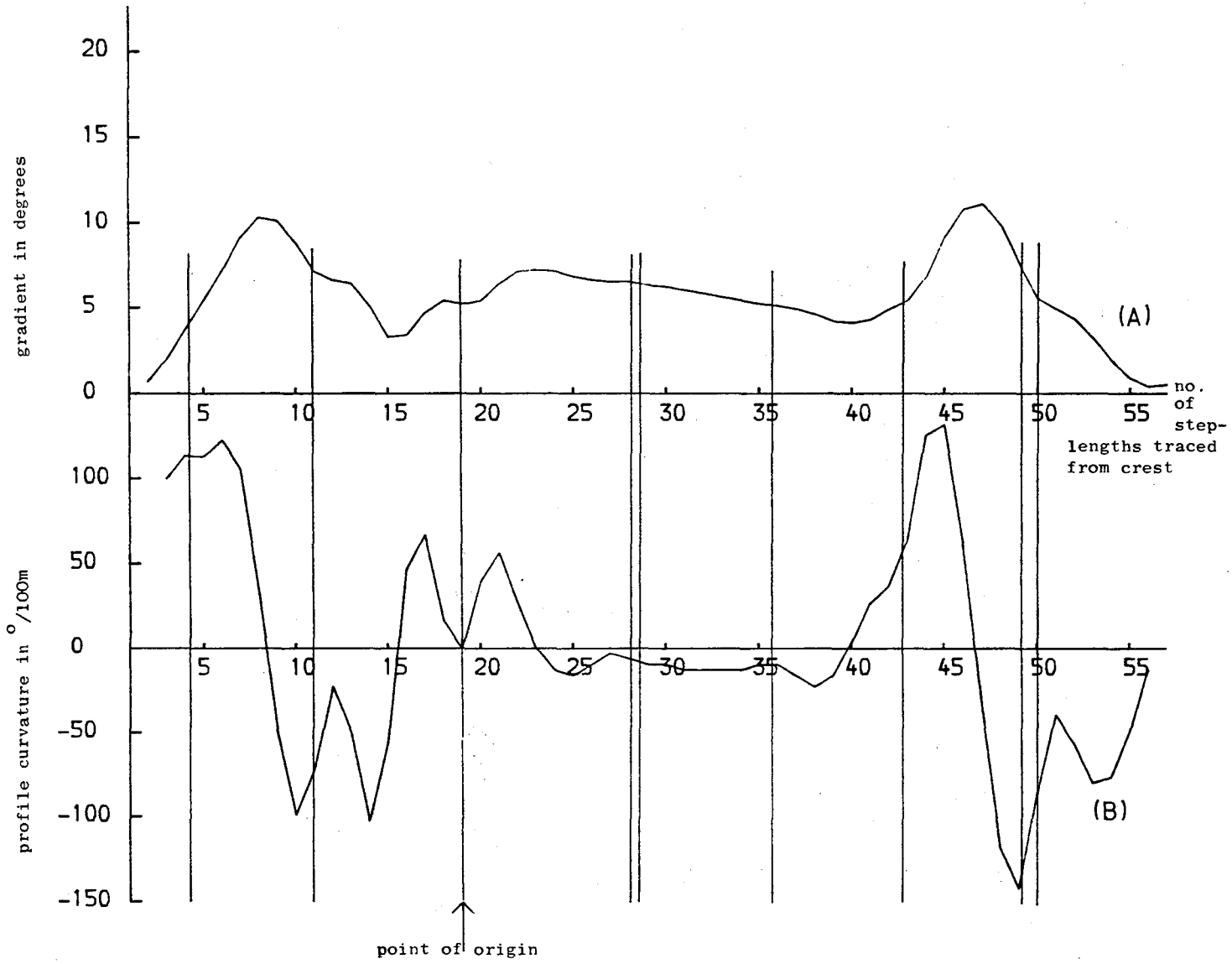


Figure 8.10 : Plots showing variation of (A) gradient and (B) profile curvature from crest to base of the Netherhearth profile at 1.5m steplength depicted in figure 8.7(C).

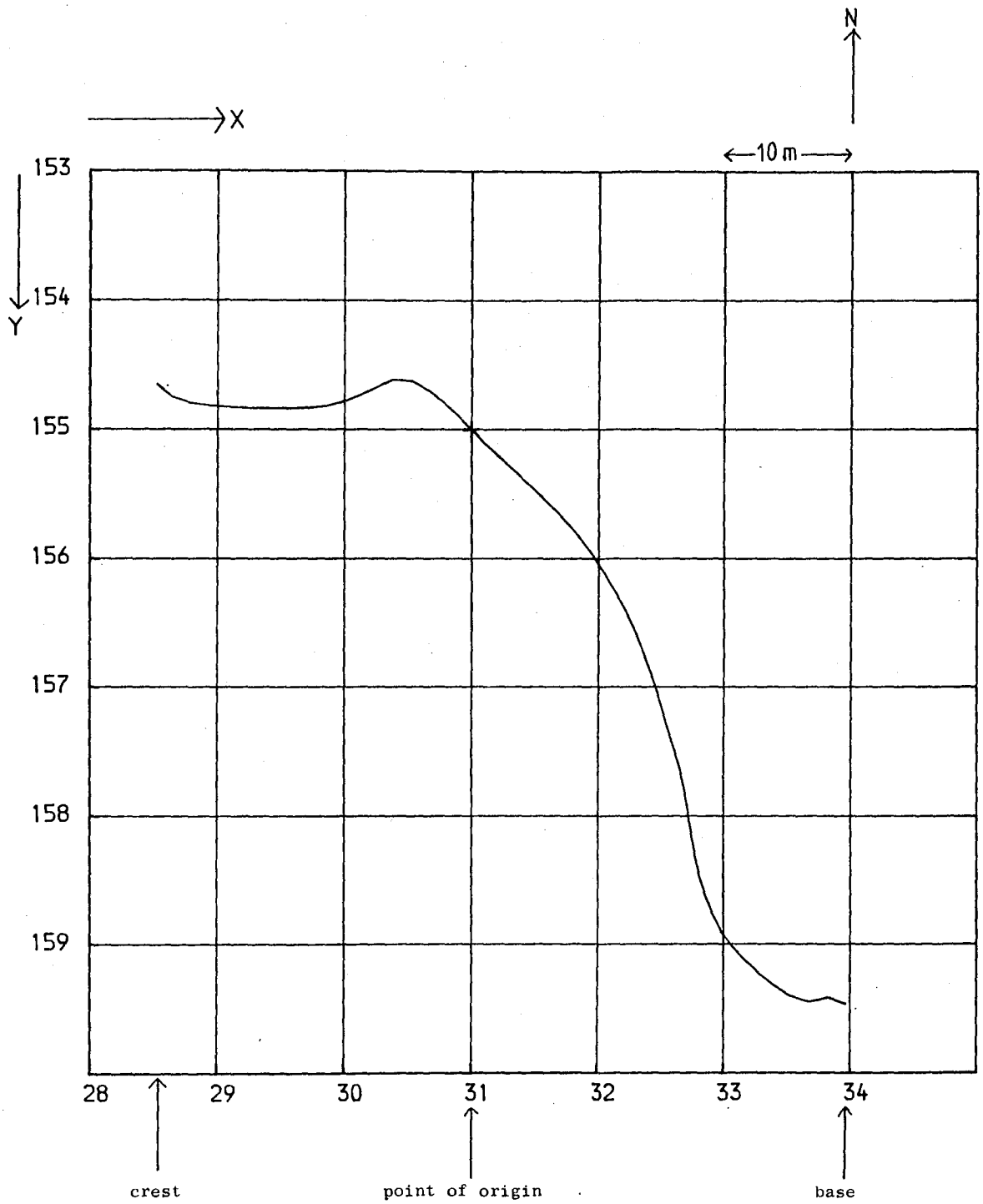


Figure 8.11 : Map of path of profile whose derivatives are plotted in figure 8.10, across Netherhearth's grid mesh.

that the latter has a grid mesh five times as broad as the Netherhearth's. Therefore in relative terms, the Netherhearth is a more ill-behaved catchment, as the wildly varying profile curvature values in figure 8.10 illustrate. The estimations of curvature at the central point of the square by the four quadratics also bear this observation out : they are 20, -82, 90 and 18°/100 m , making a range of 172°/100 m .

To test the hypothesis put forward here, that derivatives were most ill-behaved in final squares where quadratics disagreed most in curvature terms, the overlapping quadratics in a Netherhearth square that did not cause bulging of derivatives was investigated for comparison with the results quoted above for ill-behaved squares. A well-behaved Netherhearth square is that beyond steplength 28 on figure 8.10; profile curvatures as estimated at this square area's central point by its quadratics 1, 2,3 and 4 were respectively -9, -7, 6, and -17°/100 m . This is a range of 23°/100 m , several times less than that of 172°/100 m of the ill-behaved Netherhearth square. Although the former is a wider range than that quoted above for the ill-behaved Gara square, at 8°/100 m , Gara squares have 50 m dimensions while the Netherhearth's grid mesh is only 10 m : relatively small disagreements in curvature between neighbouring quadratics in the Gara assume greater absolute significance as the mathematical approximations to terrain surfaces are stretched over the large distances between control altitudes at vertices.

The investigations presented above for the Gara and Netherhearth have demonstrated that the individual overlapping quadratics agree to a large extent in altitude at the central point of their square area of mutual validity, but that the more sensitive curvature statistic is variably estimated by them. An interesting further test was to compare the altitude at an altitude matrix vertex as estimated by the quadratic

centred on that vertex, and as estimated by the three other quadratics centred around the same final square. Results are presented for the ill-behaved Gara and Netherhearth squares already discussed, in table 8.4

Table 8.4 shows that for the Gara square, disagreement in altitude estimation by the four quadratics at the vertices of the square is on average slightly greater than at the centre of the square (quoted above as 0.65 m). In one case (for vertex 2), it is very nearly twice as great, which is what one might have predicted on the basis of an assumption that quadratics become less accurate away from their centroid, because vertex number 2 is at least twice as far from vertices 1, 3 and 4 as each is from the centre of the square; however, for the other three vertices disagremeent was smaller than this. For the Netherhearth square, disagreement in altitude as estimated by the four quadratics at vertices was less than at the centre of the square (also quoted above, at just under 0.60 m) in all cases. On this evidence, it would seem that quadratics become less accurate towards the centre of a final square, rather than simply becoming less accurate with distance from their origin. It must be the case that, because the quadratics are fitted to the original altitude matrix data at vertices, they are most accurate at or near to these points, and least accurate at the centre of the square where distance to a control altitude is at a maximum. The weighting function takes account of the former by allowing most weight to the quadratic that has its origin nearest, when determining altitude at some point within a final square (such that at the vertices of the matrix, the altitude is completely determined by the quadratic centred on that point in SLOPROFIL.2, while the contribution of the other three quadratics centred around the final square has been allowed to shrink to zero). However at the

Table 8.4 : A comparison of altitude estimation (in metres) by quadratics at their point of origin and at distances equal to one mesh length or more away. (Compare down columns)

(For illustrative diagram see figure 4.5)

A) For the ill-behaved Gara square

Estimated by quadratic surface no.	Altitude at vertex number 1	2	3	4	range
1	159.715	154.026 (+)	159.512 (+)	153.365 (-)	6.350
2	158.970 (-)	153.281	159.631 (+)	154.093 (+)	6.350
3	159.647 (-)	152.789 (-)	159.444	153.958 (+)	6.858
4	159.935 (+)	153.077 (-)	159.377 (-)	153.890	6.858
range	0.965	1.237	0.254	0.728	

B) For the ill-behaved Netherhearth square

Estimated by quadratic surface no.	Altitude at vertex number 1	2	3	4	range
1	603.656	602.148 (+)	603.829 (-)	602.447 (-)	1.681
2	603.500 (-)	601.993	604.254 (+)	602.210 (-)	2.261
3	603.741 (+)	601.964 (-)	603.915	602.466 (+)	1.951
4	603.706 (+)	602.238 (+)	603.903 (-)	602.455	1.665
range	0.241	0.274	0.425	0.256	

Note : altitudes underlined have been estimated by a quadratic at its origin and therefore form the yardstick against which the other altitudes down a column of the table may be compared. + or - underneath the other altitudes indicates whether they exceed or under-estimate the yardstick altitude.

centre of the square, the weighting function uses the average of the four estimates of height by the four quadratics, although none of these is at its most accurate here. First and second derivatives of the weighted average surface have been shown in this section to be sensitive to the relative lack of control in this area of each surface, in that they sometimes show an upward or downward bulge towards the centre of a square.

The ranges in altitudes of the four vertices, shown in the right hand columns of both tables in table 8.4, are in all cases a great deal larger than the differences in altitude estimation at vertices or at the central point of a square by the four quadratics. That is to say that the magnitude of real altitude differences over space dwarfs the magnitude of the errors in estimation of altitude at a point. This is as it should be.

The overall precision and bias of altitude estimation by SLOPROFIL.2 at the centres of JNJ-fitted squares was assessed by comparing altitude estimated at the centres of JNJ squares fitted to the Gara matrix at 100 m mesh, with the original 50 m mesh altitudes available for the same points. For a sample of 2593 such points covering the Gara catchment, the average altitude calculated by SLOPROFIL.2 was 0.011 m lower than the actual altitude from the 50 m matrix, with a standard deviation of 2.807 m. The low mean difference shows that SLOPROFIL.2 is an unbiased estimator of true heights, but the standard deviation reveals some lack of precision. The skewness of this distribution of differences (SLOPROFIL.2 altitude minus real altitude) was 0.754, indiating a tail towards high positive residuals. These are likely to occur where SLOPROFIL.2 underestimates the depth of a valley, which is likely with 100 m matrix data which does not provide many sampling points with which to estimate the position of a linear feature.

8.4 Conclusions

The conclusion from section 8.2 is that derivatives of the land surface are sensitive to scale of measurement : the fact that we are dealing with mathematical approximations to terrain rather than measuring the terrain itself directly in the field,does not exempt us from this truism in geomorphometry. Gradient is a great deal less sensitive than profile curvature however, so that gradient may be used to determine appropriate terminating conditions for matrix-based profiles. Profile curvature can only be used when the appropriate steplength to yield values comparable to those from G has been determined.

It was also shown in section 8.2 that standard deviation of gradient and profile curvature were over-estimated by samples of profiles generated by SLOPROFIL.2 for which other statistics agreed with G. The investigations in section 8.3 have shown that in the real terrain of the Gara and Netherhearth, a set of four quadratics which overlap in a final square do not give the same values for surface curvature at the central point of that square, where they are all given equal weight by Jancaitis and Junkins' function used in SLOPROFIL.2. At or near to an altitude matrix vertex, derivatives obtained by G and by SLOPROFIL.2 could expect to be similar because the quadratic centred on that point which is wholly used to determine the G values, is also given most weight by the J and J function. However further away from any vertex, the surface dealt with by SLOPROFIL.2 is a different thing from that dealt with in G : in the former case it is an average of four surfaces whose curvatures seldom agree. Irregularity due to this is picked up with increasing sensitivity by higher derivatives of the surface : that is, gradient and profile curvature. Altitude is encouragingly robust : its standard deviation is well estimated by profiles from SLOPROFIL.2, and its value at the central point of a

final square as estimated by the four quadratics centred at that square's corners disagrees by about 0.6 m for both Gara and Netherhearth catchments, having mesh sizes of 50 m and 10 m respectively. Profiles produced by SLOPROFIL.2 (e.g. figures 8.7 (A) and (C)) show no distortion.

The irregularity of the behaviour of second derivatives (e.g. figure 8.5) within final squares is somewhat unsatisfactory. This thesis has shown that contour orthogonals following realistic paths and looking realistic in a plot of altitude versus distance, can be generated on such a surface; but clearly the bumpiness in derivatives interferes with SLOPROFIL.2's ability to produce statistics consistent with G's. This problem was unforseen, and it is difficult to determine theoretically what type of local surface would generate a more even surface. Fitting linear instead of quadratic surfaces would probably eradicate the bulging, but other artificiality might be introduced by approximating patently non-planar terrain by a set of overlapping planes. Jancaitis (1975) says that more experimentation is needed to test the performance of surface-fitting functions : he found that the weighting function as used in this thesis gave acceptable contours from UNAMACE data when applied to overlapping linear surfaces. To this writer's knowledge nobody has tested the ability of a surface made up of locally-valid patches to sustain realistic contour orthogonals. There are reports of other suitable surface-fitting routines in the literature (e.g. Akima (1974 a & b), Sibson and Thomson (1981)), and it is suggested that somebody who required better performance in second derivatives than SLOPROFIL.2 as constituted at present can supply, could investigate the effect of replacing the relevant parts of the program with an alternative surface-fitting routine.

The perfect performance of SLOPROFIL.2 on mathematically-defined altitude matrices (plane and parabola) shows that there are no errors in the program. It also illustrates graphically the point that it is never sufficient to test a surface-fitting algorithm solely on artifical data. The important thing to test for is good behaviour when dealing with the sort of real surfaces that the program is going to have to work on. It is clear from the tests carried out in this chapter that SLOPROFIL.2 performs better on fine-mesh matrices where no part of a final square is far from a control point, and on smooth topography where four neighbouring quadratics are less likely to give radically different estimates of curvature.

8.5 Notation

a,b,c,d,e	coefficients of a quadratic equation (see chapter 4)
θ	angle between line joining a point to the origin of a quadratic, and the line Y = 0 of that quadratic
r	distance of a point from the origin of a quadratic
X	one of two perpendicular coordinate directions in the horizontal plane; increases from West to East
Y	one of two perpendicular coordinate directions in the horizontal plane; increases from North to South
Z	approximation to height of real terrain achieved using functions in X and Y

CHAPTER 9 : FURTHER VALIDATION OF THE METHOD, APPLIED TO A LARGE CATCHMENT: FERRO, S.ITALY

9.1 Introduction

9.2 Grid scheme

9.3 Profile sampling baseline scheme

9.4 Talweg and divide scheme

9.5 Conclusions

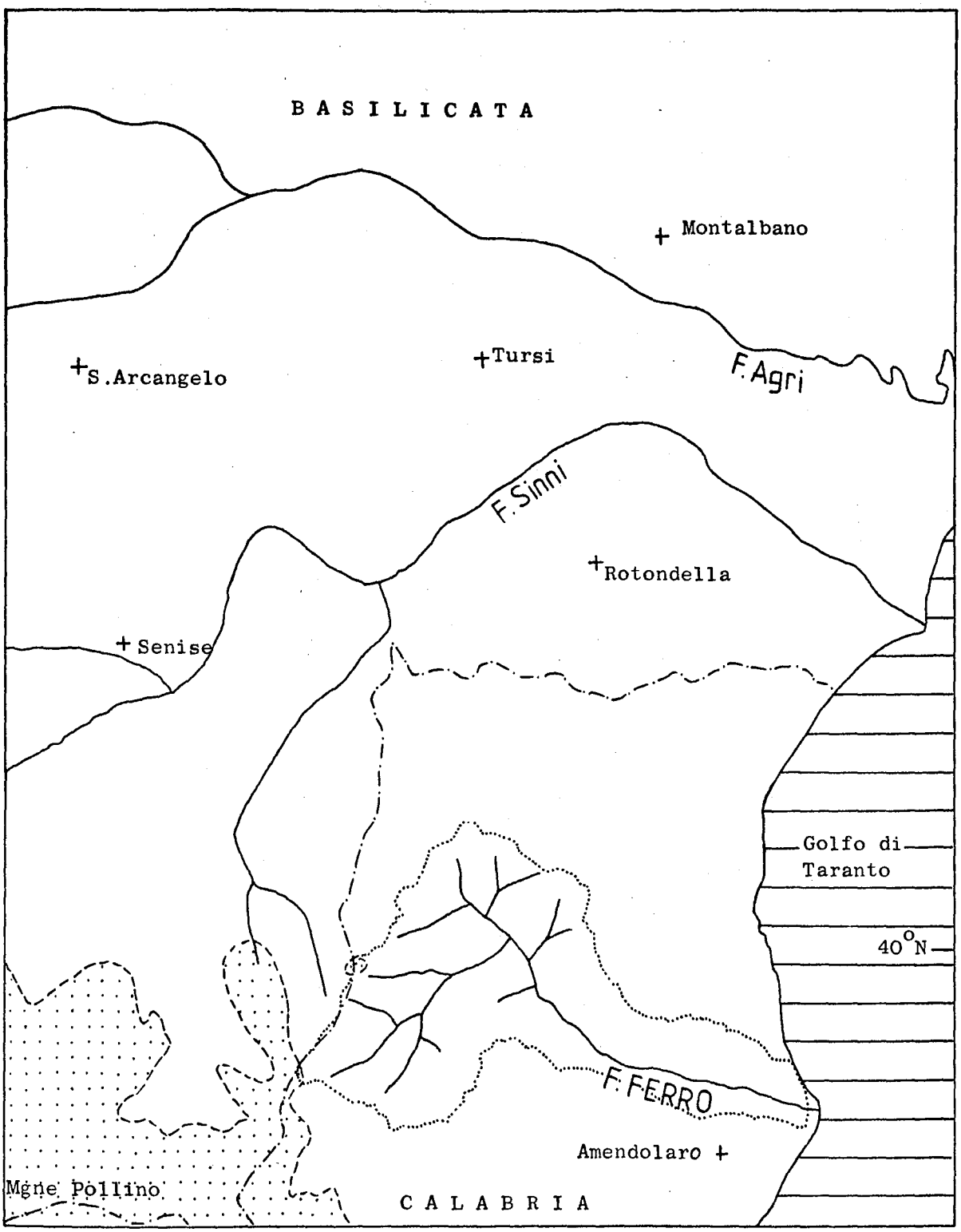
9.1 Introduction

So far the method, of drawing profiles through matrices with SLOPROFIL.2 and comparing summary statistics with those from a uniform sample of point-based values from matrices analysed with G, has been tested on two British drainage basins. Some of the ideas for the procedure in SLOPROFIL.2 came out of experience gained during fieldwork in those two catchments. The success of the method of profile construction in the two very contrasted areas (in terms of topography, fluvial development and scale) is encouraging, but it is also important to ensure that the program SLOPROFIL.2 can easily be applied to any area for which an altitude matrix exists.

The comparison of grid and PSBL to define profile points of origin was only possible in the Gara catchment, since it was considered impossible to construct a PSBL in the relatively undissected topography of the Netherhearth catchment. The two sampling schemes are compared in a second catchment in this chapter. It is also desirable to see if improved results can be obtained from a sampling scheme extended from talwegs and divides interpolated directly from the matrix, rather than separately from the source map as was the case in the Gara.

The third catchment chosen was the Ferro catchment having an area of about 118 km^2 in North Calabria, Italy, whose location is shown in figure 9.1. An altitude matrix had already been made of this area at 100 m mesh from 1:10,000 scale maps having a 10m contour interval. The altitudes had been encoded to the nearest 10m - a much coarser interval than the recording to the nearest 2 feet of Gara altitudes, for example - and it was an interesting test to see if SLOPROFIL.2 would be sensitive to any artificiality imparted by this.

Evans, who has already discussed the analysis of this matrix



KEY

province boundary

river

land over 1000m

towns

coastline and sea

watershed of Ferro

0 10km

N

Figure 9.1 : Map showing location of the Ferro in southern Italy.

by G, says of the region that it is 'sharply dissected and without summit plateaux : the only extensive level areas are the floodplains of the Ferro and its main tributaries, which are braided and choked with sediment' (1979, 75). This is a more completely dissected topography than either the Gara or Netherhearth, and it was judged that the PSBL might perform better in such an area. Hillslopes in Ferro are dissected by numerous gullies however, so that in detail the topography is not simple.

One important change was made in the analysis of Ferro statistics. Profile curvature was transformed to 2/3.14159 (arctan (0.12 profile curvature)), to give a shorter-tailed distribution of this attribute. This was because its moment-based summary statistics had been found (e.g. in the previous chapter) to reflect a few extreme values in the long tails of the untransformed distribution.

9.2 Grid scheme

Rows, 2,3 and 4 of table 9.1 show that profile lengths (right-hand column of table) in this catchment are sensitive to the value of GLOBAL (overall orientation change in profile) used to terminate profiles in SLOPROFIL.2; the value of ORCJ (local orientation change) was satisfactory at 10° throughout, as in the Gara catchment. Rows 2,3 and 4 also show that mean gradient decreases with increasing value of GLOBAL, as in the Gara catchment, although in the latter there were large areas of low-gradient summit to cause a long profile to give a lower figure for mean gradient, whereas in the Ferro catchment this is not the case. The lower gradient with increasing GLOBAL for Ferro must be partly due to longer profiles traversing more low-angled talweg, as figure 9.2 bears out. Figure 9.2 also shows that the longer profiles are more like those that a fieldworker would survey than the

Table 9.1 : Summary statistics from computer profile sets generated in Ferro catchment and located according to various sampling schemes

Sampling scheme (value of GLOBAL in brackets)	Altitude (m)			Gradient (degrees)			Profile curvature (transformed)		No. of profiles	Average profile length (m)
	mean	st.dev.	skew	mean	st.dev.	skew	st.dev.	skew		
1) 100 matrix with G	445.16	211.44	0.39	13.07	5.04	0.04	0.330	0.126		
2) grid (35°)*	438.91	202.16	0.38	13.55	5.90	0.53	0.444	0.105	107	764.80
3) grid (40°)*	436.51	198.05	0.35	13.21	5.88	0.52	0.440	0.100	107	863.05
4) grid (45°)*	436.88	195.27	0.33	13.06	5.96	0.56	0.441	0.106	107	941.85
5) grid (45°)*	425.24	191.78	0.32	12.53	6.09	0.66	0.452	0.101	56	883.65
6) grid (45°)*	444.91	180.91	0.46	13.13	5.29	0.23	0.445	0.092	31	1055.50
7) grid (45°)*	463.47	200.38	0.71	13.07	5.83	0.48	0.446	0.033	19	1057.65
8) PSBL (45°)	452.63	175.56	0.23	12.98	5.48	0.36	0.428	0.074	98	858.85
9) PSBL (45°)	449.70	178.94	0.11	12.43	5.11	0.33	0.421	0.093	48	942.80
10) PSBL (45°)	443.63	169.34	0.41	12.34	5.23	0.17	0.431	0.136	19	888.95
11) divide (45°)	448.60	160.94	0.31	12.92	5.50	0.33	0.434	0.075	45	704.90
12) talweg (45°)	458.62	174.26	0.86	13.34	6.00	0.97	0.432	0.037	90	585.85

Note : steplength used in all computer profiles was 5m

* Profile sets analysed with weighting applied such that each profile received a weight of 1. (In cases not marked with an asterisk, each steplength received a weight of one)

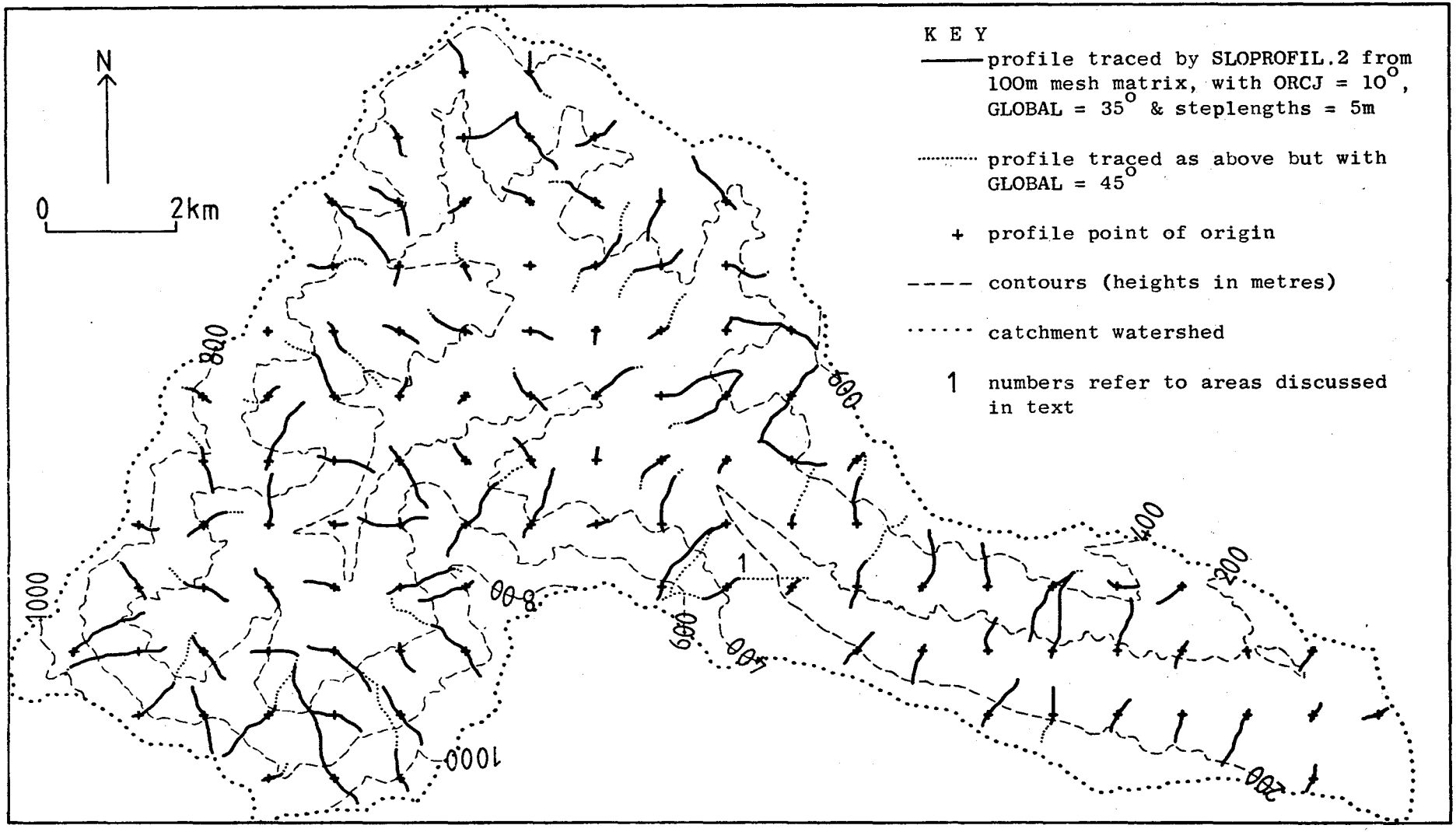


Figure 9.2 : Map showing extension of Ferro profiles achieved by a 10° increase in GLOBAL.

shorter (GLOBAL = 35°) ones, as they more usually extend from crest to base of the slope: see the improvement of the GLOBAL = 45° profile over the GLOBAL = 35° one from the same point of origin on the slope marked with a '1' on figure 9.2 (in the lower valley, just above the 200m contour).

It should be noted that there are a number of plain (flat) areas in the matrix, particularly near to the mouth of the Ferro, which arise partly due to the coarse (10m) encoding interval used for this matrix. The statistics from these points are omitted from the G results presented here, as such plains are not the subject of hillslope studies and SLOPROFIL.2 could not traverse them, because aspect is indeterminate in no-gradient areas. Figure 9.3 shows that profiles have largely avoided the talweg area between the locations marked '2' and '3'.

Figure 9.3 demonstrates that the catchment is well covered by a dense sample of grid-scheme profiles using the terminating conditions (ORCJ = 10°, GLOBAL = 45°) found to give best agreement with G's mean gradient statistic (row 1, table 9.1) for a large profile sample (row 4). There do not appear to be any oddities in these profiles due to the coarse encoding interval; the steep relief of the area must minimize its effect.

Profiles do not reach quite to the catchment watershed in figure 9.3 because this matrix did not include any altitudes for vertices <u>outside</u> the watershed, and so the layer just inside it could not be fitted with quadratic or weighted average surfaces. This unsampled area is not therefore a result of any deficiency in profile sampling. To ensure that weighted average surfaces can be fitted by SLOPROFIL.2 to all areas up to and including the watershed, the operator should encode altitudes for a double layer of vertices outside the catchment all the way round.

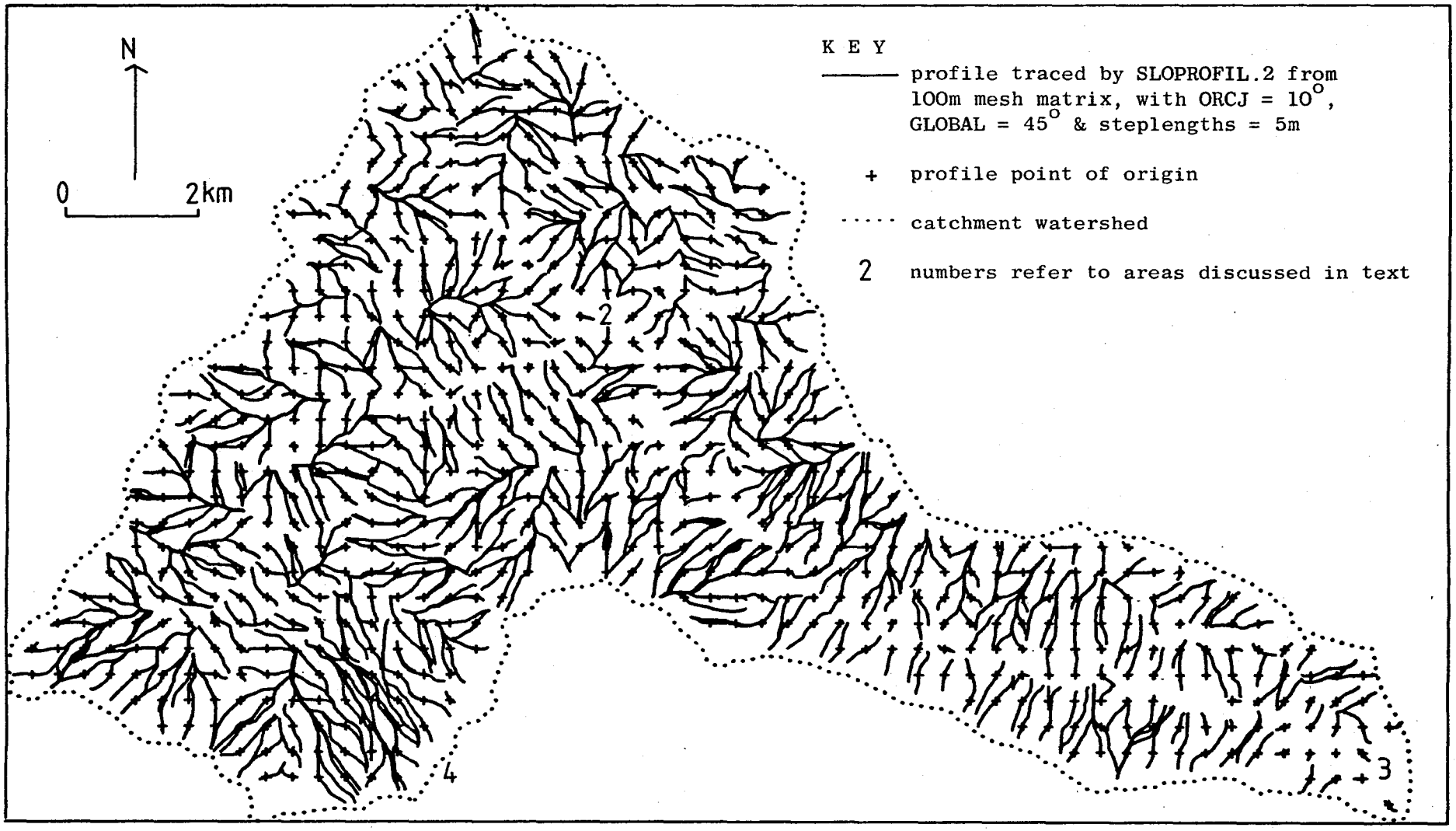


Figure 9.3 : Map showing coverage of Ferro catchment by 678 grid scheme profiles.

Rows 5, 6 and 7 of table 9.1 show the effect on statistics of decreasing the number of grid scheme with GLOBAL = 45° profiles generated in separate runs with SLOPROFIL.2. The results indicate a greater tendency for altitude and mean gradient statistics to vary between 107-, 56-, 31- and 19 - profile samples than was found between similar sample sizes in the Gara catchment (table 7.2), which must reflect Ferro catchment's greater size and lesser homogeneity than the Gara's. Thus the 56 - profile sample in Ferro (row 5 of table 9.1) underestimated G's mean gradient by half a degree, whereas that from the 107 - profile sample (row 4) agreed with G's mean gradient. The 56 - profile sample also gave shorter profiles on average than the larger one. Samples of 31 and 19 profiles (rows 6 and 7) agree more closely in mean gradient with G however, and profiles are even longer on average than those of the 107 - profile sample in both these cases.

The 56 - profile plot is reproduced in figure 9.4, while that of the 31 profiles is shown in figure 9.5. It can be seen that several of the profile points of origin in the former fall in areas from which a long profile is not sustained, whereas this is a rare occurrence in the latter. This is evidence that 56 profiles is a small number with which to sample this large and complex catchment, and it cannot therefore be guaranteed that <u>any</u> 56 points of origin defined by a regular grid will give rise to even sampling of the land surface types by profiles. On the other hand the 31- and 19- profile samples come markedly nearer to G's mean gradient than the set of 56 profiles, suggesting that <u>some</u> smaller samples are able to give more reasonable coverage due to more fortunate positioning of points of origin with respect to the land surface types. The 31-profile sample yields good estimates of G's mean altitude and standard deviation of gradient also.

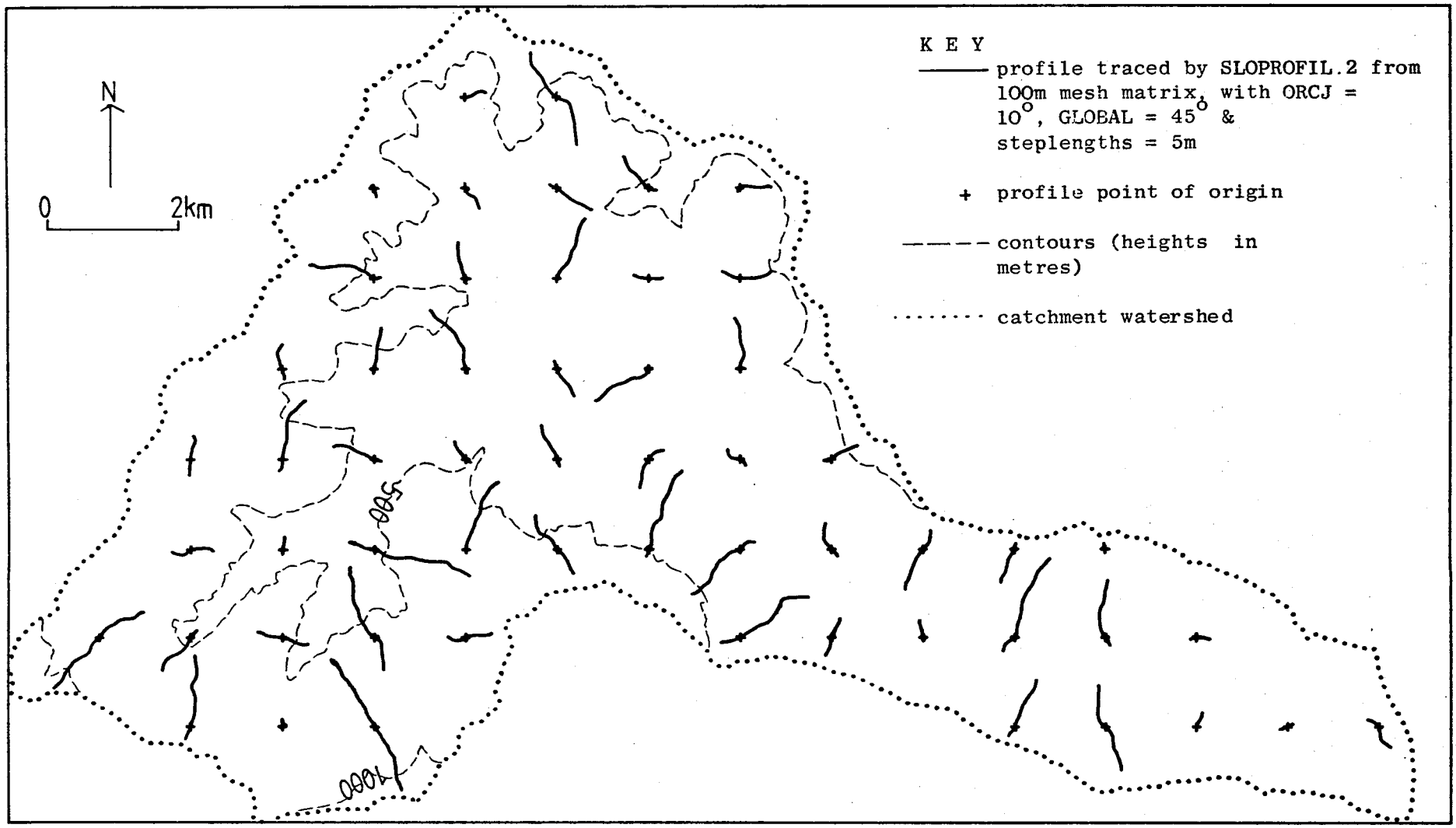


Figure 9.4 : Map of 56 grid profiles.

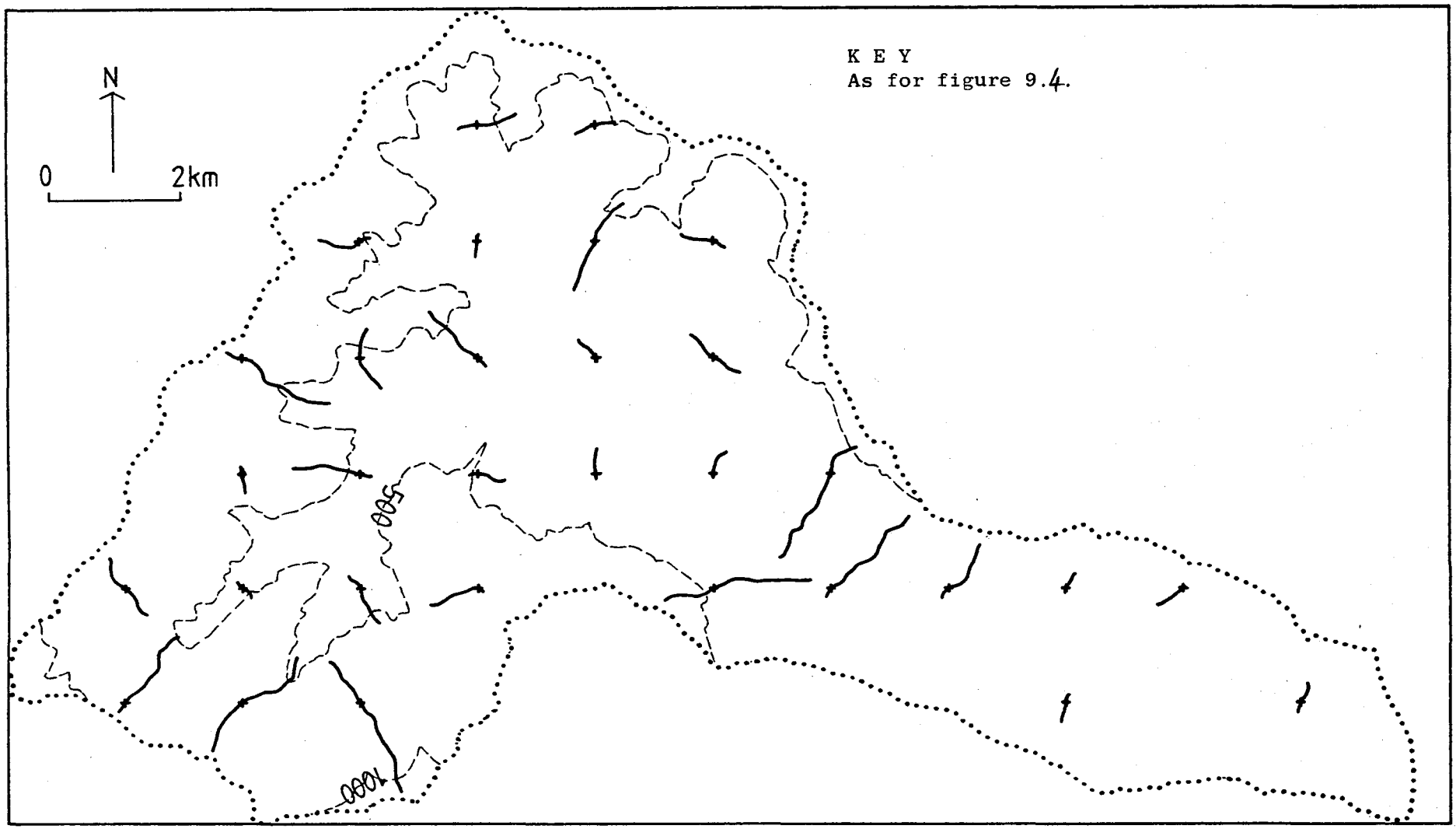


Figure 9.5 : Map of 31 grid profiles.

Figure 9.6 shows that altitude increases from mouth to south-western headwater of this catchment. Profile-based altitude statistics are bound to be sensitive to the exact spread of profile points of origin over this range, regardless of how long the profiles are. The thin strip of land towards the mouth of the catchment presents a problem similar to that at the mouth of the Netherhearth : with wider sampling nets, profiles are likely either to miss it out completely or else to oversample it, depending on the exact incidence of the grid. This explains some of the variation in altitude statistics in rows 4 to 7 of table 9.1.

Mention must be made of standard deviation of gradient and of (transformed) profile curvature. As in the Gara, the 5m-steplength profiles presented for Ferro all overestimate these two parameters in G. Clearly the bumpiness of derivative values within weighted average squares in SLOPROFIL.2, discussed in the previous chapter, is also manifested in Ferro - which is not surprising given the coarse grid mesh. The fact that altitudes were encoded to the nearest 10m probably caused neighbouring quadratics, representing a least-squares fit to this stepped data, to be quite different from each other and therefore liable to give an uneven weighted average surface. The sensitivity of standard deviation of profile curvature to scale is preserved in the transformed values : for example from use of 30m steplengths a value 0.06 smaller than that from 5m steplengths was obtained.

Row 1 of table 9.2 presents summary statistics from the very large grid profile set depicted in figure 9.3, to enable comments to be made on the stability of statistics from large (i.e. 107, see table 9.1 row 4) and very large (678) profile sets. Mean altitude agrees more closely with G's for the 678 - profile set, as does skewness of

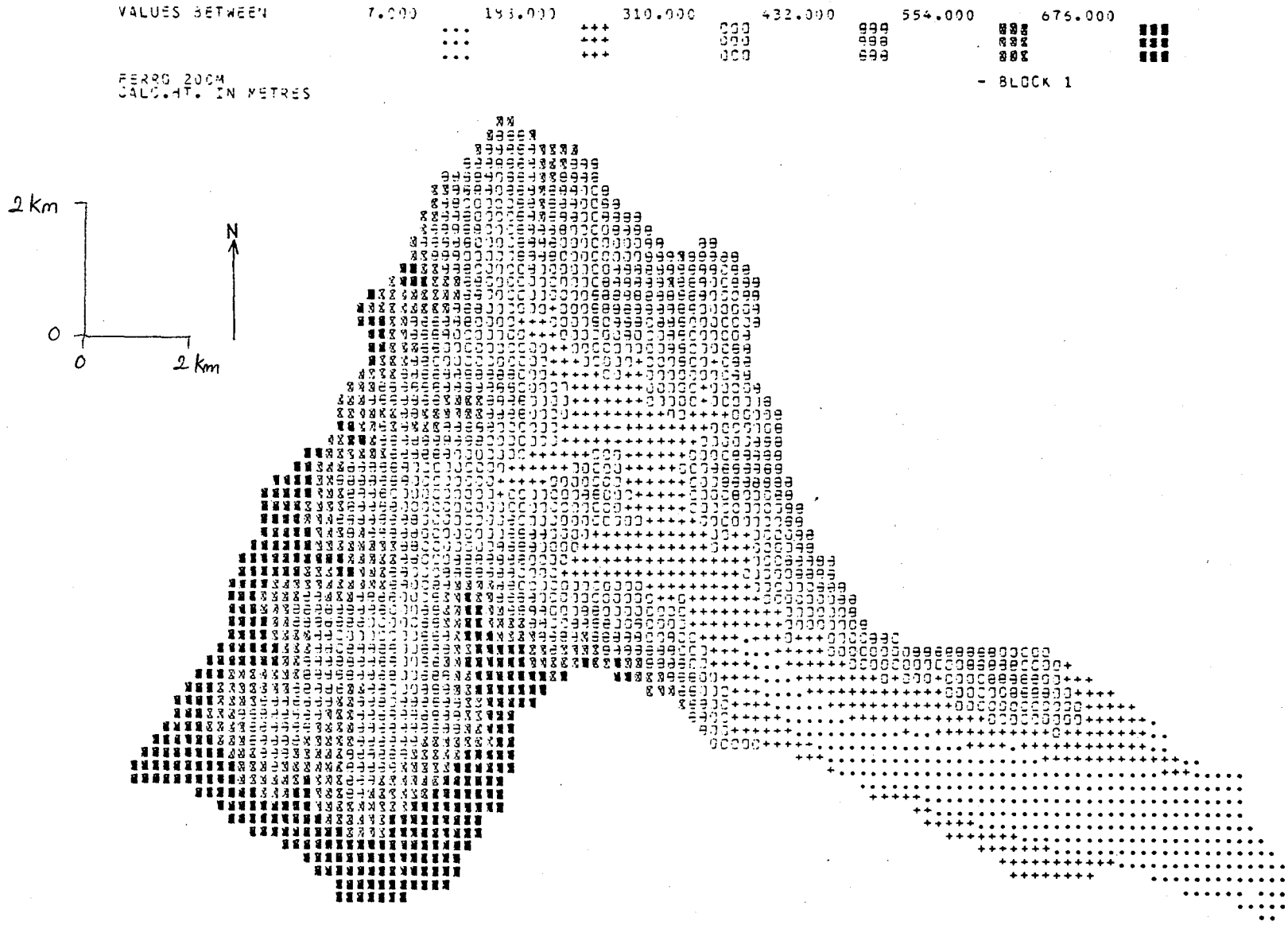


Figure 9.6 : Map of altitude in metres in Ferro catchment, from the matrix at 200 m mesh (Each character on the map refers to the centre of a square of 200 m dimension therefore)

Table 9.2 : Summary statistics from large computer profile sets generated for Ferro catchment

(All profiles generated with ORCJ = 10°, GLOBAL = 45° & steplengths = 5m)

Sampling scheme	Altitude (m)			Gradient (°)			Profile curvature		Average profile length (m)	No. of profiles	CPU time taken to generate profile set (seconds)
	mean	st.dev.	skew	mean	st.dev.	skew	st.dev.	skew			
1) grid, with each profile given weight of 1	447.29	187.41	0.43	12.96	5.74	0.66	0.447	0.101	956.20	678	251
2) grid, with each steplength given weight of 1	469.67	195.34	0.36	12.77	5.67	0.59	0.427	0.090	956.20	678	251
3) PSBL	452.61	182.59	0.23	12.96	5.51	0.45	0.432	0.071	861.65	674	230
4) divide	502.47	210.95	0.16	12.60	5.65	0.58	0.424	0.075	891.60	367	138
5) talweg	442.10	168.95	0.48	11.65	5.81	0.52	0.424	0.125	732.80	333	101

altitude; standard deviation of altitude agrees less well than for the 107 - set however. Mean gradient still agrees well with G's for the 678 - set, and standard deviation of gradient has moved closer to G's, although both profile samples over-estimate this parameter. Skewness of gradient is also well above G's for the 678 profiles : this suggests that the bulging of derivatives within weighted average squares in SLOPROFIL.2 causes the profiles to register some large gradients, so transforming the near-normal distribution of gradient registered by G into a positively-skewed one. Standard deviation and skewness of profile curvature are no better estimated by the 678 - profile sample than by the 107. Mean profile length is consistent over the change in sample size, which is encouraging.

In Gara and Ferro catchments, the most successful profile samples judged by altitude and mean gradient statistics have more positively skewed gradient distributions than G's; there is likely to be scope for eradication of this source of divergence between the two programs by transforming profile statistics therefore. Disagreement in skewness of gradient is greater for Ferro than it was in the Gara, presumably because of the broader grid mesh and coarser encoding interval used in Ferro. G's skewness of gradient was well estimated by large profile samples in the Netherhearth (table 7.3) (although smaller Netherhearth profile samples overestimated it too); this is consistent with what one would expect from a more detailed grid mesh. These findings therefore strongly endorse the suggestion that for maximum success in matching G and profile statistics from SLOPROFIL.2, one should make as detailed a matrix as the map information will allow : probably 50m mesh or more detailed.

The second row of table 9.2 shows results from the same large grid profile sample analysed without the weighting applied. The mean

altitude statistic shows that weighting is necessary: without it the longer, high-altitude headwater slopes in the catchment have been over-represented. The longest slopes cover the area marked '4' on figure 9.3, which is not the area of steepest slopes, as the gradient map (figure 9.7) shows. The greater weight allowed to these slopes in unweighted analysis must be a factor causing the unweighted sample to underestimate G's mean gradient.

The right-hand column of table 9.2 shows that it does not take an excessive amount of computer CPU time to generate these useful large profile sets : this time figure compares favourably with that taken to generate the Netherhearth matrix using GPCP, for example (chapter 3).

9.3 Profile sampling baseline scheme

Although the map from which the matrix had originally been made was available, it was fairly pointless to construct a PSBL from this as it had a preponderance of very detailed relief features (gullies), the majority of which would not be picked up by a matrix at 100 m mesh. Therefore it was judged to be more useful to make a contour map from the matrix, and construct a PSBL from that. The matrix information was therefore input to the contouring stage of GPCP (the General Purpose Contouring Program - see chapter 3) and a dense contour interval specified (25m) so that minimal interpolation would have to be performed by the operator. The map is reproduced in figure 9.8. Talwegs and divides were defined from this contour map, the former by the contour crenulation method. Then a PSBL was drawn half-way between these.

Construction of the PSBL was made easier by elimination of all the unnecessary detail on the original basemap, but there were still some difficult - and subjective - decisions to be made which affected the quality of coverage by profiles extended from it (see figure 9.9).

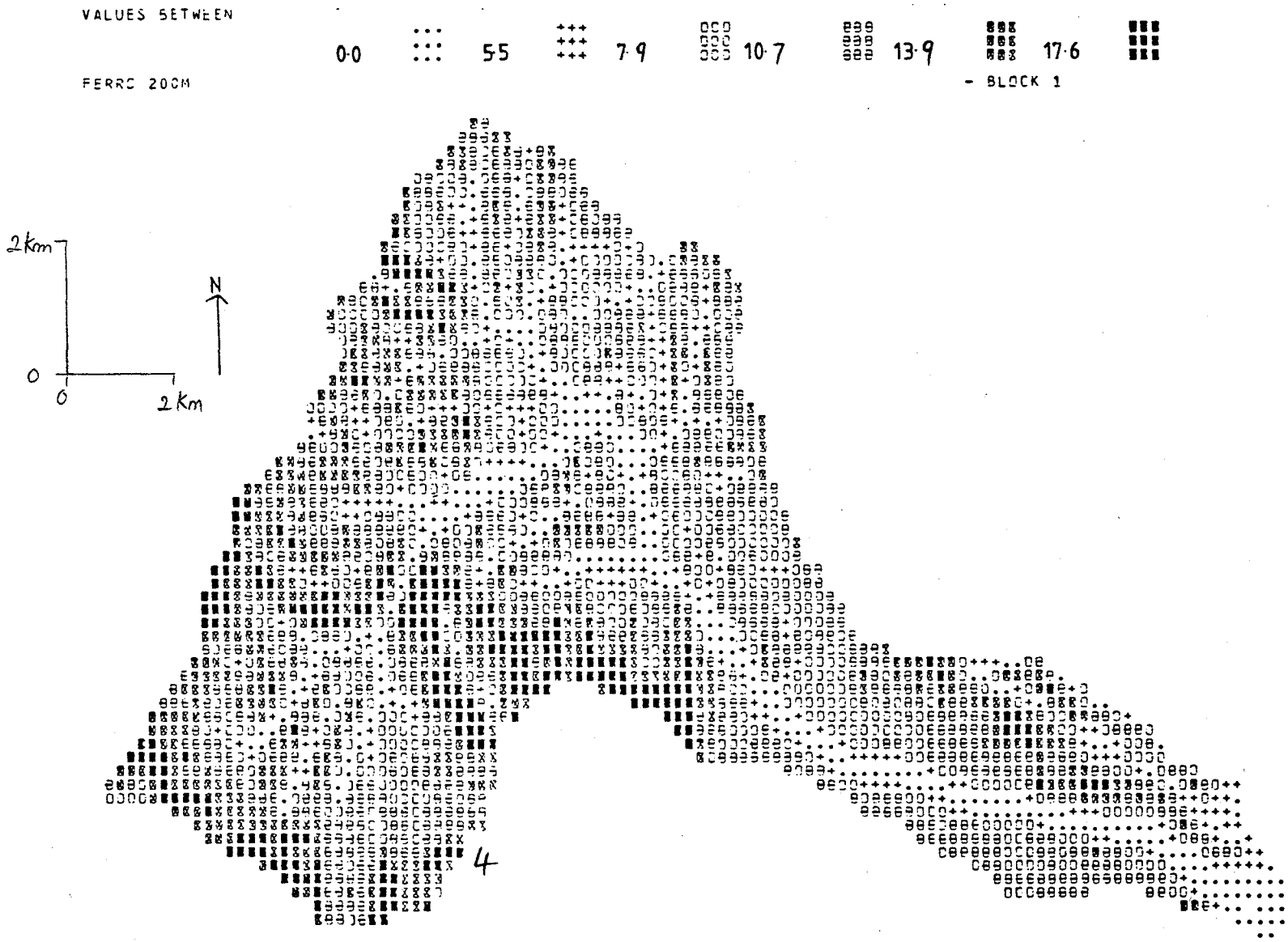


Figure 9.7 : Map of gradient in degrees in Ferro catchment, from the matrix at 200 m mesh.

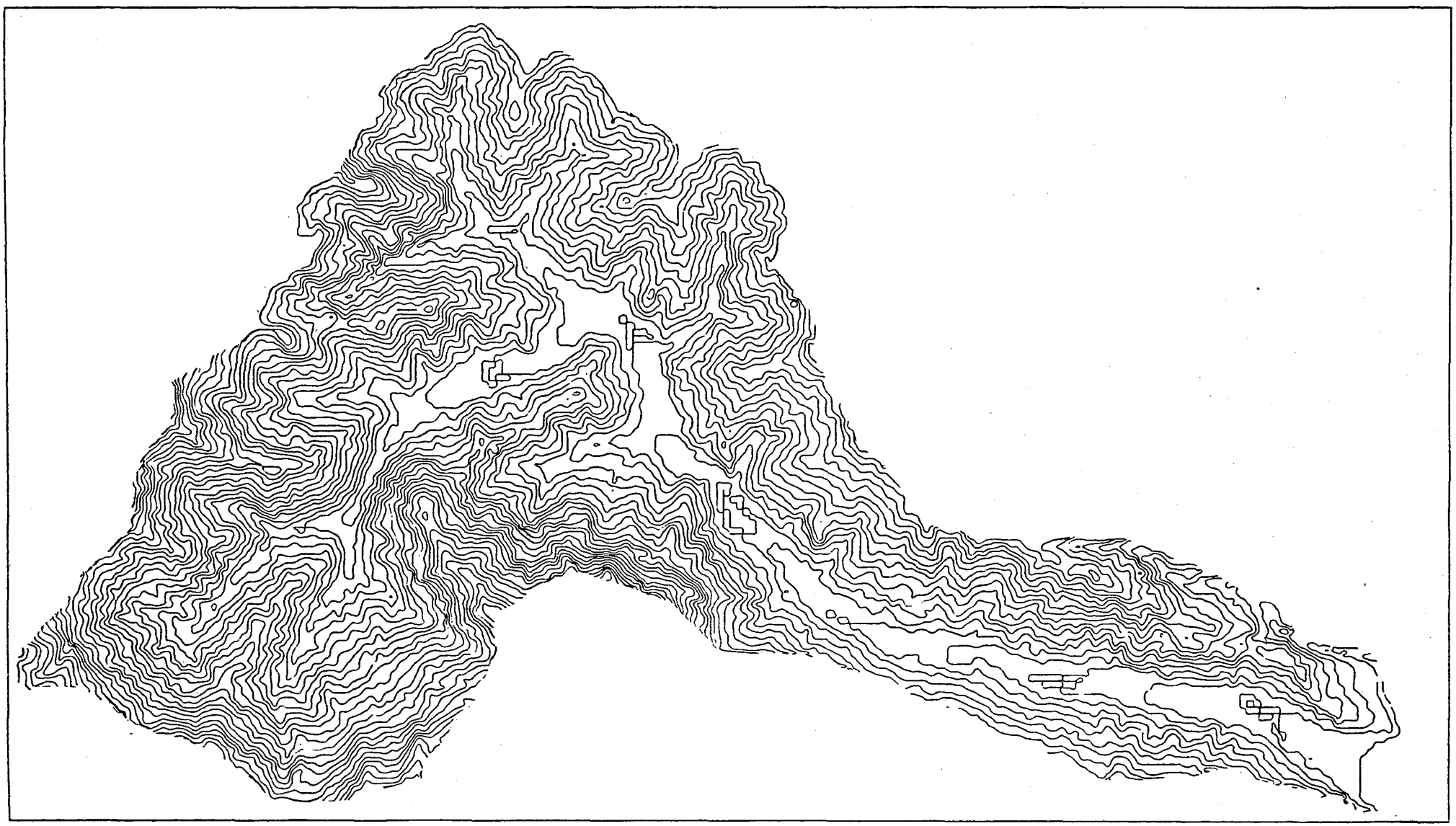


Figure 9.8 : Contour map of Ferro catchment made from the matrix at 100m mesh with 25m contour interval by GPCP.

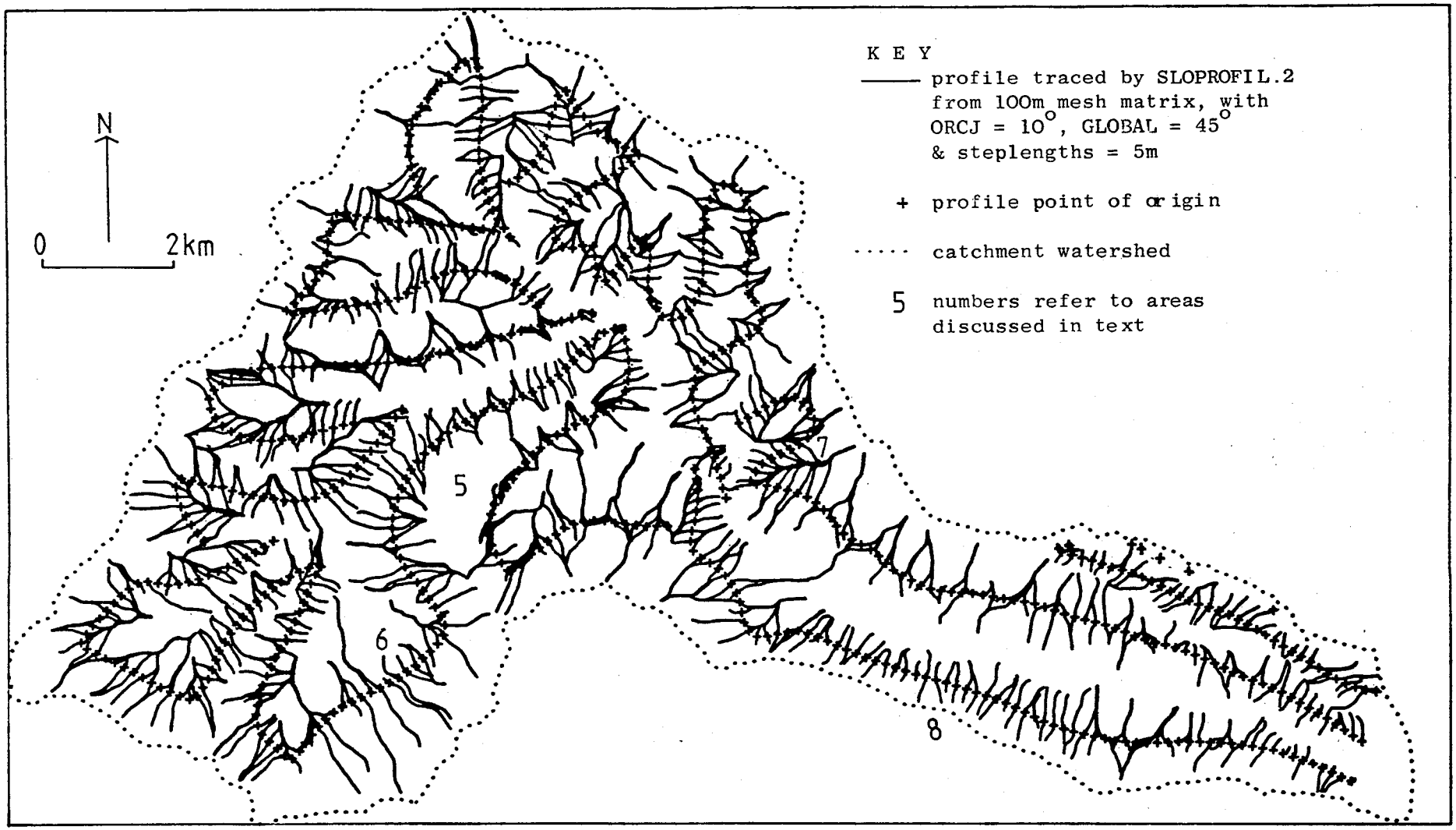


Figure 9.9 : 674 profiles generated from points of origin equally spaced along the PSBL in Ferro.

The areas marked '5' and '6' on figure 9.9 illustrate a lack of sampling by the PSBL profiles of a summit and valley bottom respectively. There is a temptation when drawing a PSBL around a large catchment to allow it to describe a broad sweep in accordance with the pattern of major slopes in that catchment, as was done in constructing the PSBL for figure 9.9. However profile paths are very sensitive to the exact configuration of minor gullies, so that profiles from a PSBL extended straight across a series of these will terminate downslope (in the gulley) before reaching the main valley floor as at '6', and also fail to reach the main valley divide due to convergence on upslope convexities separating gulley heads.

However when the PSBL was allowed to describe a large deviation around a nose slope separating two gullies, as at '7' on the figure, this led to oversampling of this steeply-plunging divide. Coverage of profiles from the PSBL was, predictably, best when the main valley slopes were straight in plan and relatively free from gullies registered by the matrix; such is the case along the slope marked '8' on the figure.

A better PSBL than this one could be established in this catchment by trial and error : digitizing different implementations of the PSBL and generating large profile samples from it. This option does however seem unsatisfactory when there is a simpler and adequate alternative (the grid scheme) available to a study aiming to achieve unbiased coverage of a surface by profiles. Comparison of figure 9.9 with 9.3 shows that the grid profiles on the latter cover the areas marked '5' and '6' on the former, proving conclusively that these are not flat areas and should therefore receive profile coverage.

Row 8 of table 9.1 shows that the estimate of mean gradient from a large PSBL profile sample with ORCJ = 10° and GLOBAL = 45° is close to G's. Standard deviation of gradient and profile curvature

are lower than in the grid scheme case, bringing them closer to G's, but it would be wrong to say that this demonstrated superiority of the PSBL coverage when the evidence presented above is taken into account. Mean altitude is greater than G's, implying oversampling of the catchment's headwater where the greatest length of PSBL occurs, but its standard deviation is smaller, due to the lack of sampling of downslope noses and upslope summits already noted. The fact that summits are not gently sloping as in the Gara, means that the PSBL profiles can undersample them without overestimating mean gradient in so doing.

As was the case for the grid scheme, a large number (674) of PSBL profiles - the set depicted in figure 9.9 - were analysed to test the stability of such profile sample results for this sampling scheme. The results are shown in row 3 of table 9.2. Comparison of these results with those in row 8 of table 9.1 shows very considerable similarity : there is shown to be no advantage, as regards estimation of G statistics, in taking a 674- rather than a 98-profile sample located by the PSBL in Ferro. The scheme clearly performs well in this regard. PSBL profiles are nearly 100m shorter than grid profiles in both large-sample cases; this is because the former have been cut short by termination in gullies that cut across the PSBL, while more grid scheme profiles were able to follow the paths of gullies, as a visual impression from figures 9.3 and 9.9 confirms.

Rows 9 and 10 of table 9.1 show that for 48 - and 19 - profile samples located by PSBL, mean gradient is underestimated. Figure 9.10 shows the adequate (98 - profile) PSBL sample while figure 9.11 shows the clearly inadequate 19 - profile sample : it can be seen in the latter figure that slopes near the catchment's divide have been undersampled.

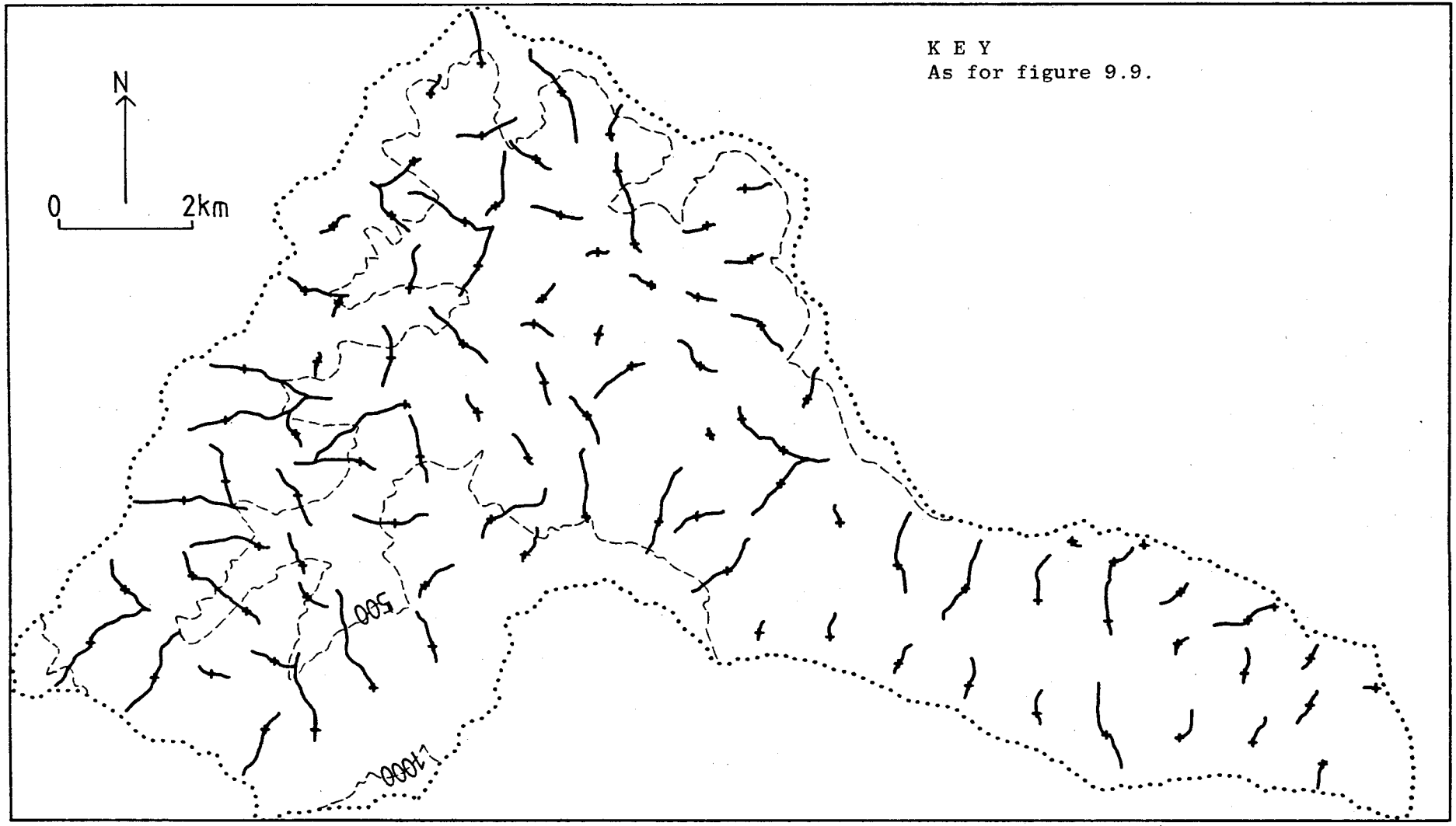


Figure 9.10 : 98 profiles generated from points of origin equally spaced along the PSBL in Ferro.

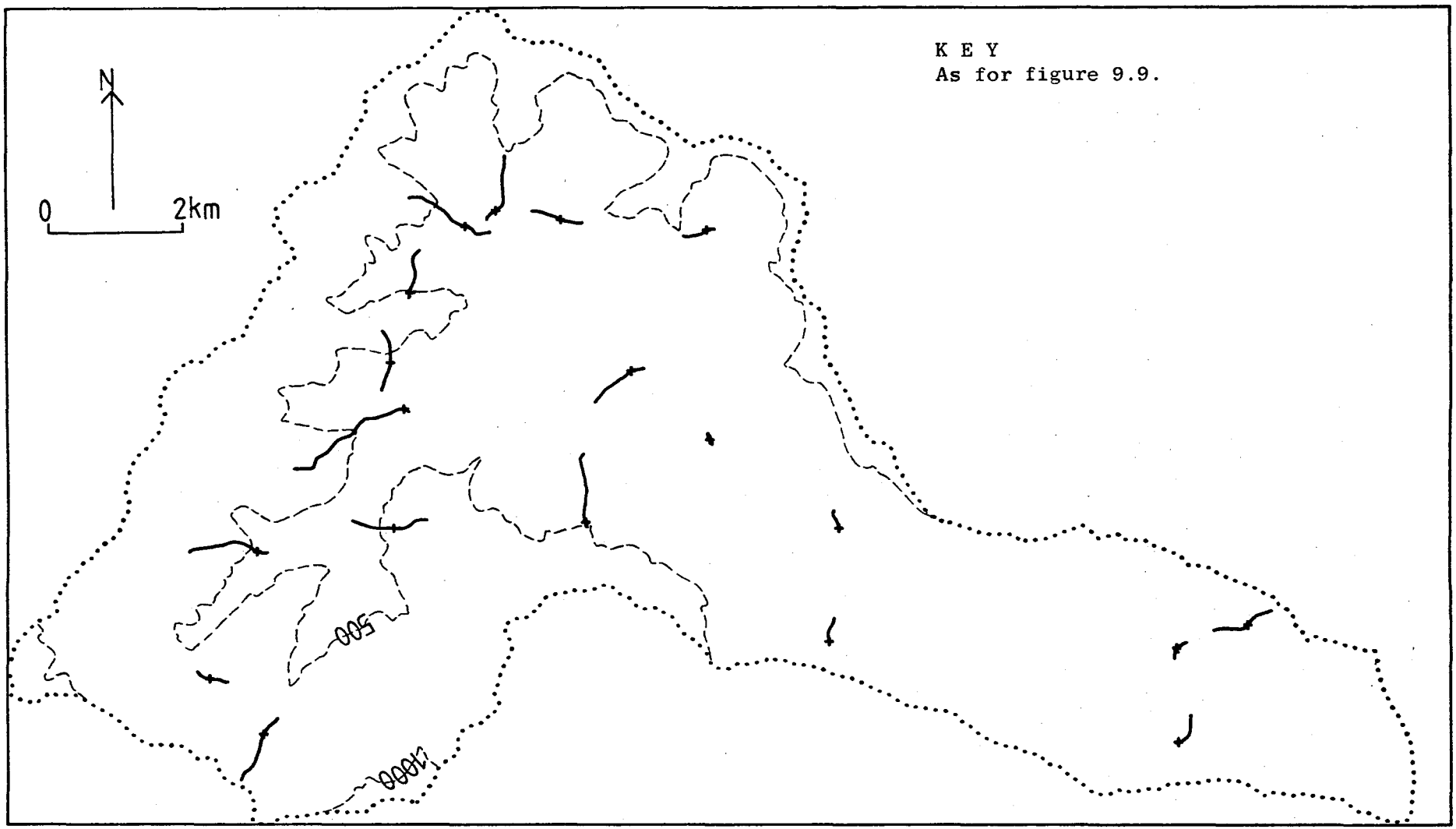
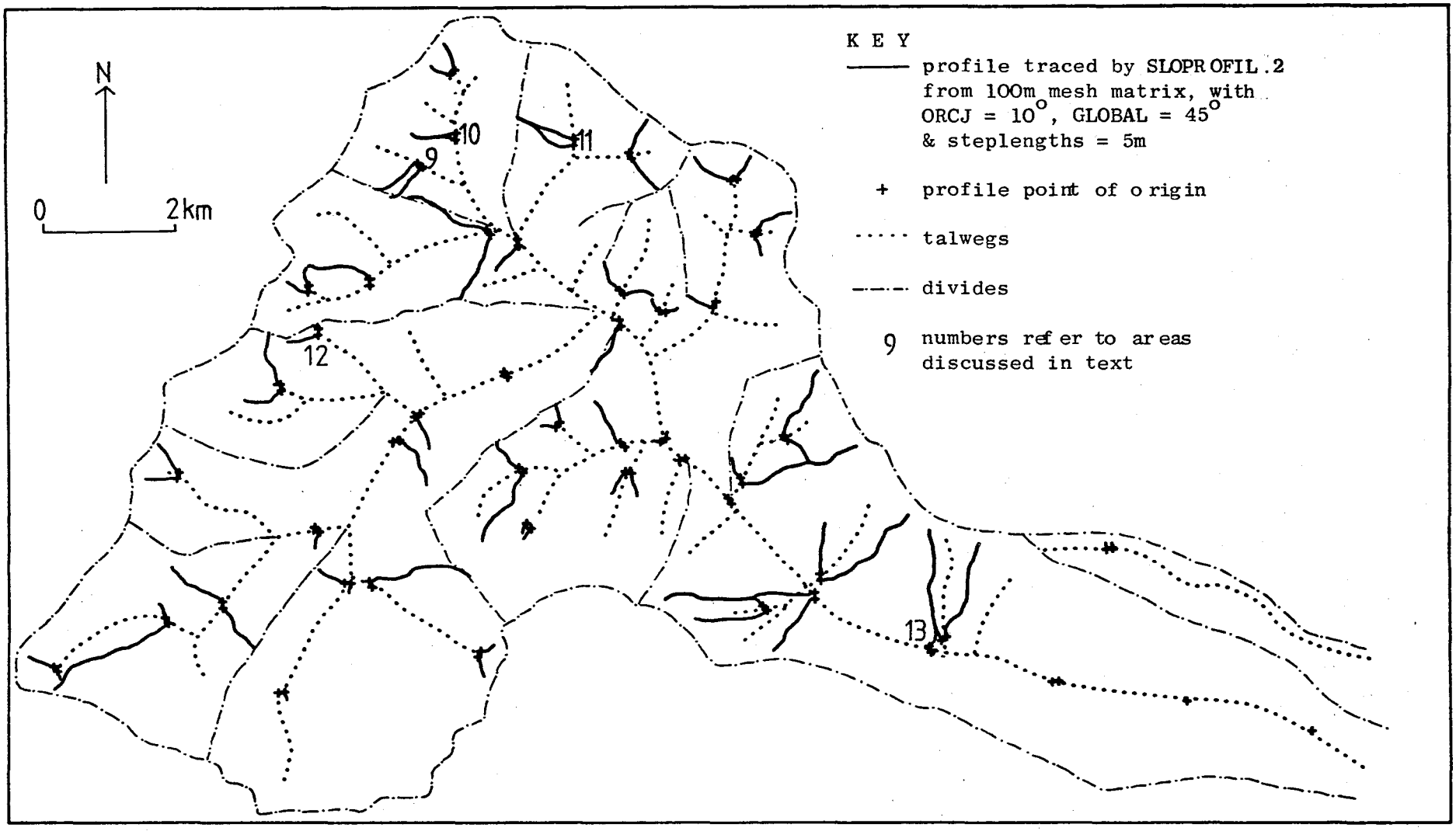


Figure 9.11 : 19 profiles generated from points of origin equally spaced along the PSBL in Ferro.

9.4 Talweg and divide scheme

In chapters 6 and 7 the results of use of talweg and divide to define points of origin were discussed for the Gara catchment. Statistics from samples of these profiles agreed with G, particularly in the divide case, but profile distribution was unsatisfactory in that paired profiles designed to traverse slopes on either side of a talweg or divide, often traversed the same slope instead. Figure 9.12, showing paired profiles commenced 50m to either side of Ferro's talwegs, demonstrates that many of the profiles do ascend opposite slopes as intended, because in this implementation, talwegs were defined from a contour map made from the matrix (figure 9.8). The points marked '9', '10' and '11' on that figure are examples of exceptions : in these cases, when the program determined the aspect of maximum slope at the talweg (following the procedure described in section 6.4iv), it was found to be in a direction at 90° to the talweg - i.e. up one of the two hillslopes on either side - so the program then defined two starting-points at 90° to that, which therefore lay along the talweg rather than on either side of it as intended. Another problem with profiles commenced at the talwegs, was that where a talweg defined by contour crenulations came very close to the divide, profiles extended from it might follow the latter, giving divide rather than hillslope profiles, as at '12' on figure 9.12.

In the Gara, points 25m on either side of divide and talweg defined the starting-places of profiles, but in Ferro this was found to give too many profiles that ascended/descended the same rather than opposite slopes. This must be partly due to the broader mesh size of the Ferro matrix. Both 50m in Ferro, and 25m in the Gara, equal half their respective matrix mesh sizes. Still it is the case in Ferro, as it was in the Gara, that the flat-floored lower valley section (down-river of '13' on figure 9.12) requires profiles that start further away



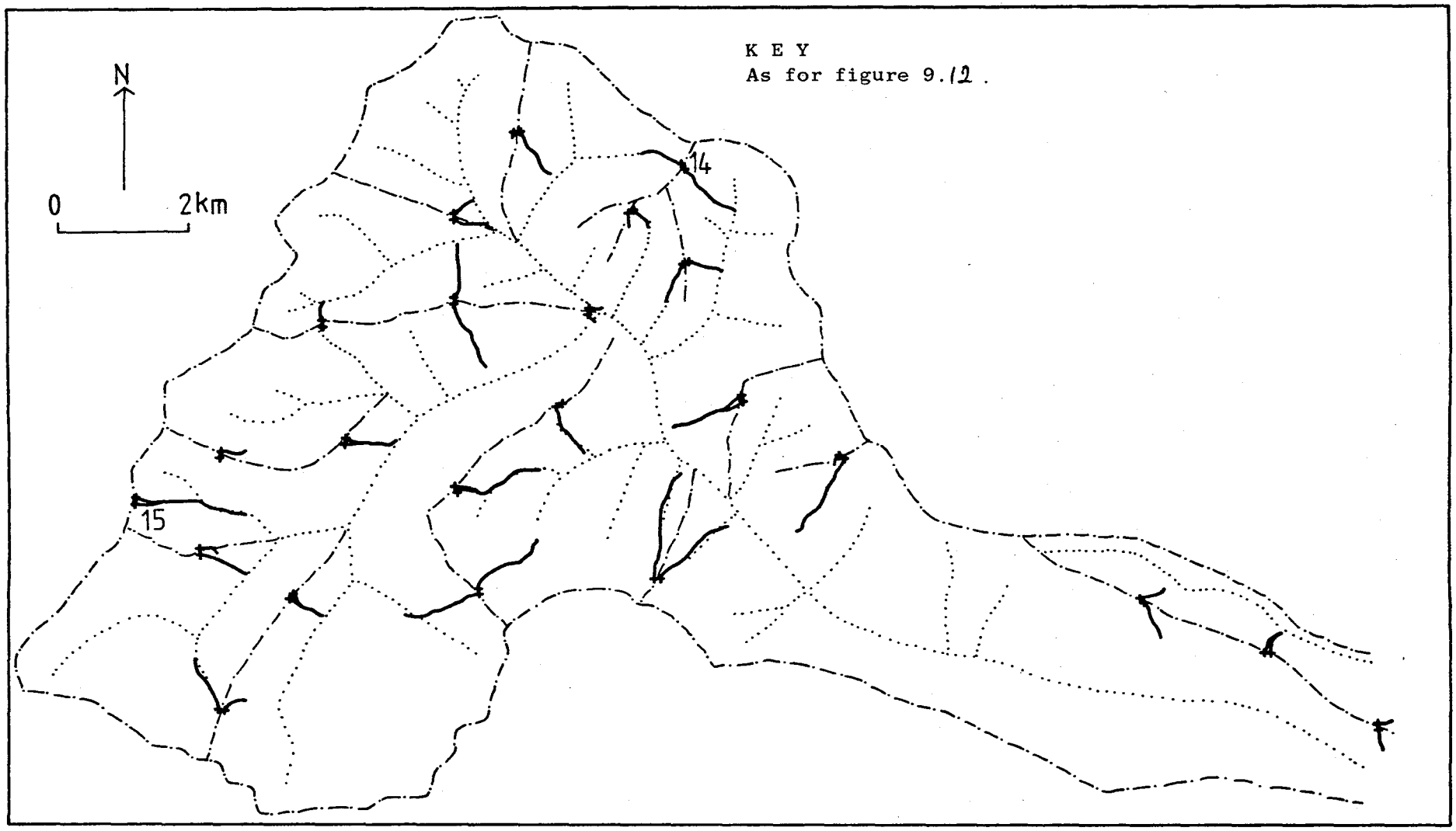
Total number of profiles = 90

Figure 9.12: Paired profiles commencing 50m on either side of the talwegs in Ferro, and tracing only upslope.

from it on either side than is the case with narrower tributary valleys. In the former areas there is a chance however that profiles extended from divides will make up for the deficiency in sampling by talweg profiles.

The slope marked '13' on figure 9.12 is a steeply-plunging divide, which is why a profile extended from the main valley floor, and one starting in the tributary gulley bottom close by, coalesce and follow it. This illustrates the problem with profiling in topography where some tributary streams are not deeply incised into the main valley slope - a problem encountered in fieldwork in the Gara as mentioned in chapter 2. If the geomorphologist preferred to measure a series of relatively short gulley slopes at about 90° to slope '13', he would have to use terminating conditions much more restricted than those used here, to avoid divide-following by profiles. If this geomorphologist were interested in studying one small sub-area of Ferro catchment in detail, such an option would be acceptable; but if the object of geomorphological enquiry were the whole catchment, then interest would inevitably focus on the broader aspects of the relief, in which slope '13' is seen less as a gulley divide and more as a hillslope profile leading from talweg to main valley divide.

Figure 9.13 shows that the problem mentioned in connection with areas marked '9', '10' and '11' on figure 9.12 was more often found with the divide option, presumably because divides in this catchment are narrower than talweg floors and do not necessarily plunge at all. The scheme gives a perfect result at '14' on figure 9.13, but by contrast at '15' on the same figure a very poor profile pair have been defined : both descend the same slope because the divide was not plunging, and the two coalesce after some distance, and end up following a talweg in addition! Single divide profiles would definitely be preferable to the



Total number of profiles = 45

Figure 9.13 : Paired profiles commencing 50m on either side of the divides in Ferro, and tracing only downslope.

paired option used for figure 9.13 : after all it is less frequent practice for geomorphologists to measure profiles on either side of a divide than on either side of a talweg.

The statistics from these profile sets (table 9.1 rows 11 and 12) show that mean gradient is fairly well estimated by both with terminating conditions the same as found successful for grid and PSBL profiles. The effect of combining these two rows would be to give a mean gradient figure in very good agreement with G's. Both talweg and divide profiles are short compared with those generated from grid and PSBL points of origin. They jointly overestimate mean altitude and underestimate its standard deviation, as profiles from them are more likely to be found in the headwater area of the catchment having more numerous tributary streams.

The option of taking paired profiles on either side of the talweg or divide as defined at 90° to the maximum descent direction <u>at</u> the talweg/divide was developed during work on the Gara catchment where divides and talwegs are broad and plunge more at their centres than the bases/crests of their flanking valleysides. However figures 9.12 and 9.13 have shown this not to be the case in Ferro, particularly for the divides. Therefore, to investigate coverage by a very large sample of talweg and divide profiles, profiles were generated from points of origin located by them in the ordinary way - that is without use of the special stream and divide option. The resulting profiles are shown in figures 9.14 and 9.15.

Figure 9.14, portraying the talweg case, shows that for all the profiles along the main valley floor it is essential to employ some method to get profiles to start away from the talweg. Several profiles continue for a short way along the talweg and then stop due to violation of ORCJ or GLOBAL by the winding valley floor; these are not

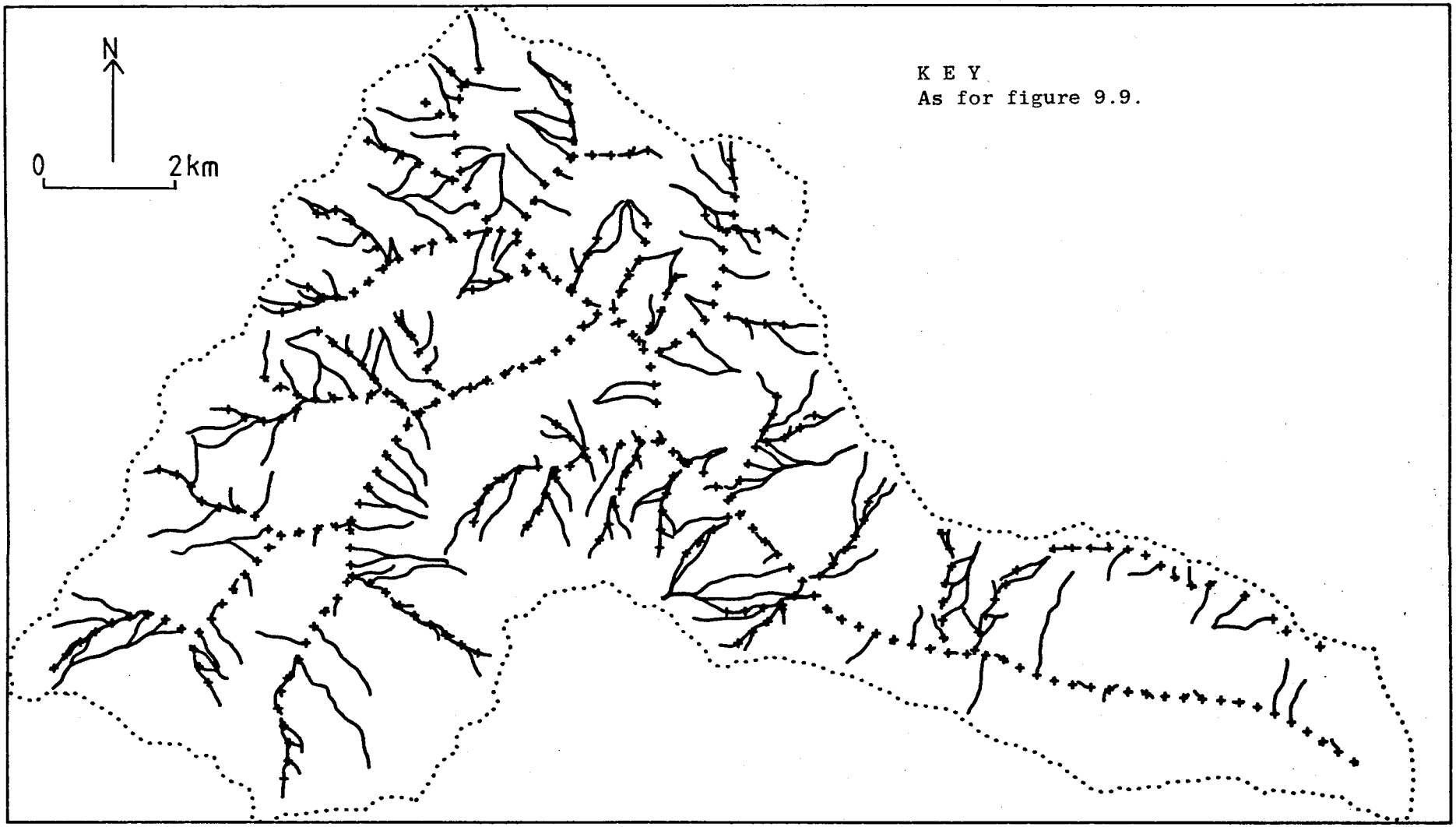


Figure 9.14 : 333 profiles generated from points of origin equally spaced along the talwegs in Ferro.

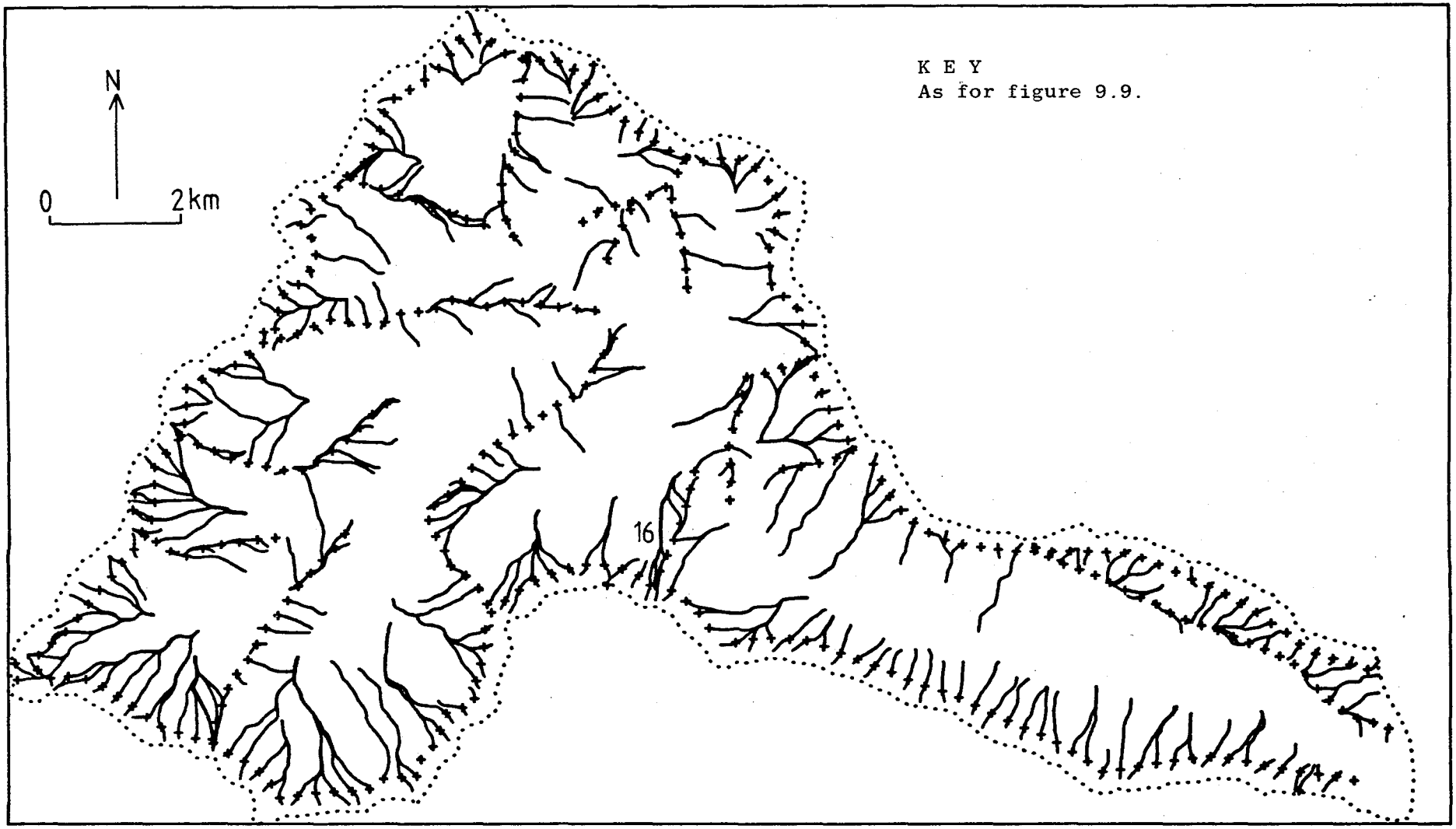


Figure 9.15 : 367 profiles generated from points of origin equally spaced along the divides in Ferro.

hillslope profiles in any sense. By contrast figure 9.15 for the divide case shows more promising results : in this case the acting catchment watershed was redefined some distance inside the actual watershed, because not enough points had been encoded outside the watershed to allow surface-fitting round the latter as was explained earlier (which is why few profiles extend from this area in figure 9.13). Profiles extended from this inner-divide give good coverage of the catchment's peripheral slopes, and there is clearly no need for a paired option here. However the plunging nature of some divides separating small tributary valleys, as at '16' on figure 9.15, makes for oversampling by the several profiles that commence on such a plunging divide. The combination of figures 9.14 and 9.15 in figure 9.16 provides a much more acceptable coverage than either on its own, which is encouraging.

Statistics from the runs that produced figures 9.14 and 9.15 are displayed in rows 5 and 4 respectively of table 9.2. Talweg scheme profiles greatly underestimate G's mean gradient, and since divide scheme profiles also do this they would not be able to cancel out this bias when used together. With the benefit of hindsight, it appears that the best way to implement a stream and divide option in SLOPROFIL.2 would be to input the digitized form lines to the program, together with instructions as to the sampling interval at which profiles should be generated from points situated on those lines. Then at each digitized point to be used as a point of origin, the program should work out the orientation of the stream/divide from the positions of its neighbouring digitized points, and define a pair of profiles to start some distance on either side by proceeding at right-angles to that direction. There would be some problems at tributary junctions, which could be dealt with by some additional statements in the program. At the moment, SLOPROFIL.2's stream and divide option is only successful where divides or talwegs are wide and slope steeply in relation to flanking valley slopes;

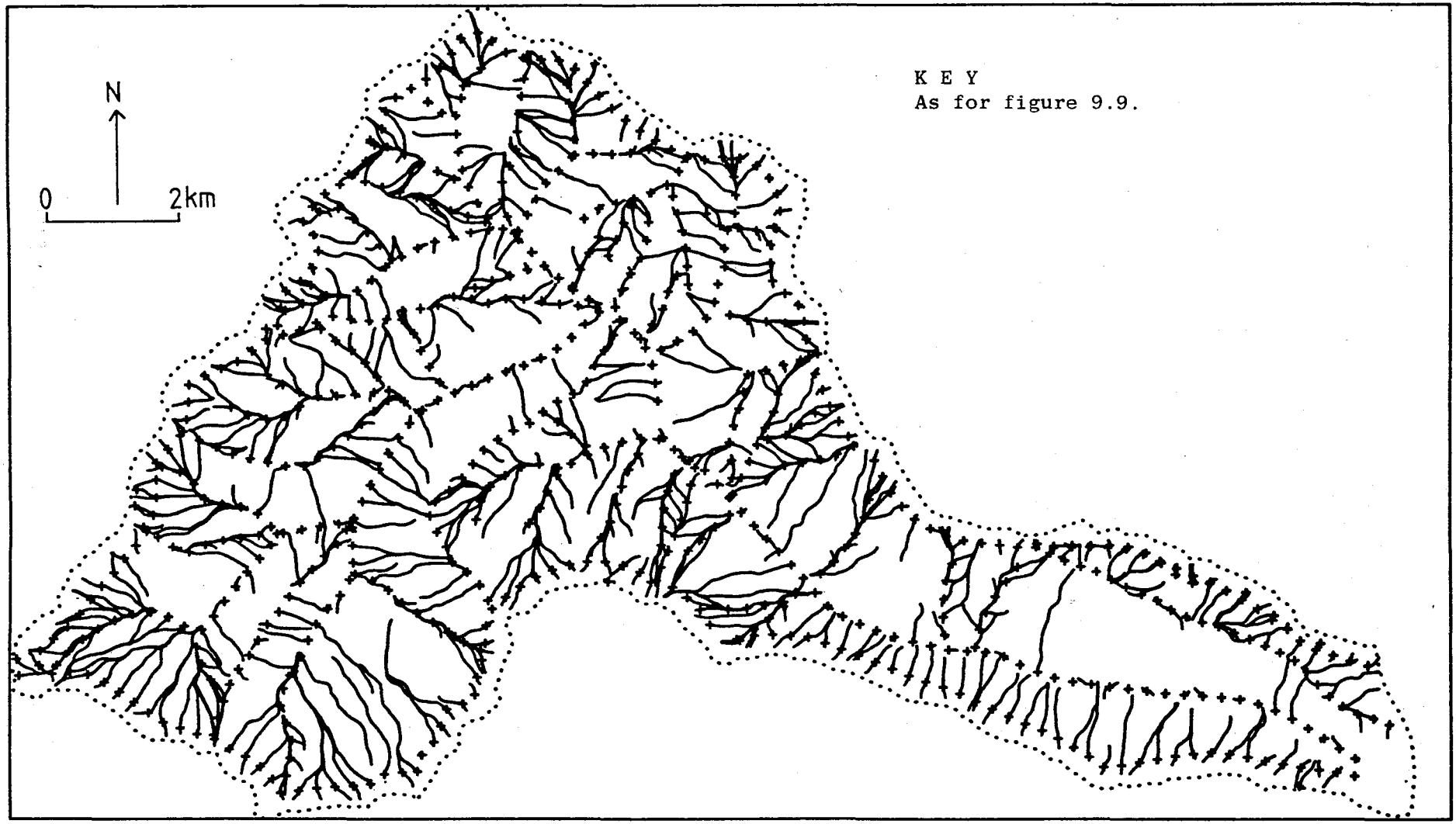


Figure 9.16 : Combination of 333 talweg and 367 divide profiles in Ferro catchment

this is more likely to be true of talwegs than of divides in well-dissected topography, as experience with Ferro confirms.

It is vital to ensure that, if the matrix does not include sufficient altitudes outside the catchment watershed for surface-fitting at the watershed, profiles can still be extended from this general area. To do this, an inner-divide should be defined some distance (three times the matrix mesh spacing is safe) inside the actual watershed, as was done for figure 9.15.

9.5 Conclusions

This examination of a new catchment has shown the program SLOPROFIL.2 to be encouragingly easy to apply in an unknown area (never visited by this investigator). It has also been shown that it is fairly easy to generate profiles over this area giving agreement with G for the statistics (altitude, mean gradient) for which comparability may be expected : the terminating conditions ORCJ = 10° and GLOBAL = 45° were able to give acceptable results for profiles starting from grid, PSBL or (paired) talweg and divide points of origin.

However although the area is simple in broad outline, it is in detail dissected by numerous small gullies, many - but not all - of which were generalized out by the broad mesh size of the matrix. This means that not all profile points of origin are able to sustain a long profile that reaches from crest to base of a main valley slope, because of the likelihood of interruption by gulley slopes. Partly due to this complexity at a more detailed scale, medium-sized (around 50) profile sample sizes could not be guaranteed to produce good surface coverage as judged by summary statistics, although for sample sizes larger than 100 both grid and PSBL scheme profile statistics displayed very encouraging independence of profile sample size.

As regards completeness of surface coverage by profiles, the grid scheme cannot be bettered - as was also the case in the Gara and Netherhearth catchments. The poor performance of the PSBL in this respect is an argument against its use, since this catchment is characterized on a broad scale by clearly-defined divides and talwegs and slopes relatively straight in plan : the PSBL will seldom encounter more favourable terrain.

CHAPTER 10 : CONCLUSIONS AND SOME SUGGESTED APPLICATIONS

10.1 Terrain modelling on computer

10.2 Implications for hydrology

10.3 Implications for slope profiling

10.1 Terrain modelling on computer

The program developed in this research, SLOPROFIL.2, which defines the paths and gradients followed by contour orthogonals through an altitude matrix, has been found to generate realistic profiles (in terms of comparability in path and gradient with the same profiles measured in the field) in the Gara catchment, where the computer profiles are generated from a 50 m mesh altitude matrix. The program is capable of terminating profiles where they encounter a change in the bearing of true slope (through the terminating conditions attached to variables ORCJ and GLOBAL), which enables it to define satisfactory slope profiles that extend from crest to base of a slope.

It has been found however that some unevenness in first and second derivatives is encountered along computer profiles generated by SLOPROFIL.2, due to the fact that neighbouring overlapping quadratic surfaces fitted to matrix data in the program often have quite different equations. When this is the case, combination of the quadratics with Jancaitis and Junkins' cubic weighting function produces a bulge or depression in first derivative values towards the centre of a grid square. This causes computer profiles to register higher values for standard deviation of gradient and profile curvature than are obtained from the quadratic surfaces analysed without the weighting function by G. This finding is not altogether surprising when one considers the unlikelihood of the terrain surface exactly matching a low-order mathematical surface over 3 x 3 altitudes. Definition of contour orthogonal derivatives is clearly more sensitive to the quality of surface fitting employed than is the definition of contours. The latter is successfully performed by several computer packages, including one using Jancaitis and Junkins' weighting function. It would be interesting to see the quality of profiles generated on some other

surfaces. In order to minimize the bumpiness of derivatives in SLOPROFIL.2, the geomorphologist should generate a matrix at as fine a mesh as possible, to give the program the maximum density of control altitudes and so limit the absolute amount by which surfaces can disagree where they overlap in the middle of a grid square.

Other results from this study have confirmed the great importance in geomorphometry of the scale of measurement. For example the Gara matrix at 100 m mesh yielded a longer estimate of optimum average profile length than the 50 m matrix, while the matrix of the same area at 150 m mesh generalized out many hillslopes so that contour orthogonals tended to follow divides and talwegs. The steplength used to trace computer profiles has some influence on gradient statistics and a greater influence on statistics of profile curvature; choice of steplength rests with the individual geomorphologist, although he may wish to follow the recommendation of 5 m made in BGRG Technical Bulletin 11.

The size of matrix mesh appropriate for any particular geomorphological study will depend on the purpose and object of that study. If a detailed record of orthogonals on an eroding peat catchment of about 1 km^2 were required (like the Netherhearth's), a 50 m matrix would not be adequate, as it would define no more than the presence of the concavity of the main stream course. A 10 m grid would provide better definition of peat flushes and minor channels; such a matrix could be plotted from air photography or (if exceptional detail was necessary) surveyed in the field, using interpolation to obtain a grid of altitudes (field survey of a grid is not recommended).

A 50 m mesh matrix was adequate to define field-surveyed orthogonals in a moderately well-dissected 27 km^2 catchment spanning 213 m of relief (the Gara). This scale of matrix can be made for

any part of Britain because of national coverage by Ordnance Survey 1:10,000 or 1:10,560 scale maps. The geomorphologist may construct such a matrix completely manually - as was done in this research for the Gara - or digitize contours and use some commonly available computer package, such as GPCP, to interpolate to a grid of altitudes. The choice between these two options depends on how closely-spaced the map contours are (great proximity makes it difficult to follow contours with a digitizing cursor without allowing them to cross over) and whether there are many nearly flat areas which tend to cause computer interpolation to create an artificial topography in the absence of unambiguous signals from control points.

In the future, altitude matrices should become more widely available as computer-assisted cartography gains ground. The production of matrices in the process of orthophotography is an encouraging development. This research has shown that there is a large amount of computer software - some developed by this researcher, some by other academic geographers, and much by the makers of computer packages - that the geomorphologist can make use of in converting these matrices into valuable tools for geomorphic enquiry.

10.2 Implications for hydrology

One aspect of this study that will be directly useful to a geomorphologist wanting to measure topography for a hydrological study, is that the method using SLOPROFIL.2 has been specifically designed to cope with all slopes, including those not relatively straight in plan. The exclusion of such slopes has been shown in this study to lead to biased surface sampling : they occupy considerable areas of the vast majority of topographies. The significance of converging and diverging flowlines for the generation of runoff has been emphasized in chapter 1 :

clearly a vital prerequisite of any morphometric method as applied to hydrology is that it be able to sample such slopes. Given that with SLOPROFIL.2, the geomorphologist can generate a set of profiles able to traverse any slope in a landscape, and that representativeness of coverage of that landscape can be gauged by agreement with G, some suggestions are made below as to how information from these profiles can be used.

As a two-dimensional approximation to the prediction of extents of surface saturation, individual steplengths along computer profiles could be classified according to 'drainability' and 'water supply' (following Speight, 1976), the former being defined by the steplength's slope and elevation potential, while the latter could be defined by the length of slope draining to that steplength. Maps of these properties over a catchment could be generated by some additional programming in SLOPROFIL.2, and would provide some grounds for comparison of different drainage basins. This approach would go some way towards answering Gardiner's (1981) plea for more functionally meaningful measurements in the drainage basin.

Another two-dimensional approach could be used to construct crude isochrones (lines of equal travel times to the drainage basin exit, after Surkan, 1969). For the throughflow phase of water travel, profiles could be constructed from the divides to end at the talwegs; then from knowledge of average subsurface permeability, plus the gradient for every steplength in each profile given by SLOPROFIL.2, travel times to the base of the slope could be computed for water falling on every steplength. The profiles could then be continued on down the talwegs to the basin outlet by setting ORCJ and GLOBAL to large values, and rates of open flow in channels applied to these lengths of profile.

Much interest in hydrological modelling focusses on the definition of area drained per unit contour length : a measure of convergence or divergence of flowlines, bringing the three dimensions of the land surface into play. An approximation to this could be obtained by defining 'unit catchment areas' using an approach suggested by Speight (1968). Orthogonals could be traced downslope from every matrix vertex, representing the downslope paths of drops of water falling at matrix vertices within or over a hillside. Then a line 30 m long (for example) and parallel to the local contours could be laid over every matrix vertex and the number of intersections it made with orthogonals could be counted. This would locate the centre of the Eastergrounds hillside hollow whose orthogonals (traced upslope as well as downslope from grid points of origin) are shown in figure 10.1. An advantage of this approach is that the grid-based data yielded by it could be added to information (on altitude, gradient, and profile and plan convexity) available for the same vertices from G. It has already been suggested in this thesis that the latter would form a useful topographic input to hydrological models like Beven and Kirkby's Topmodel.

Figure 10.1 could be redrawn by adding a net of soil water potential values, if available, to the elevation potential values used there, giving total potential. This would predict actual water flowlines in the slope regolith rather than the theoretical lines that a freely rolling ball would follow over the surface, as here. For this hollow, the modification would make little difference to flowlines as mean gradient of the profiles shown here is 8.56°, but for low-angled (less than 6°) slopes investigated by Anderson and Kneale (1980), the soil water potential pattern has been found to disrupt the water flow paths predicted by elevation potential alone.

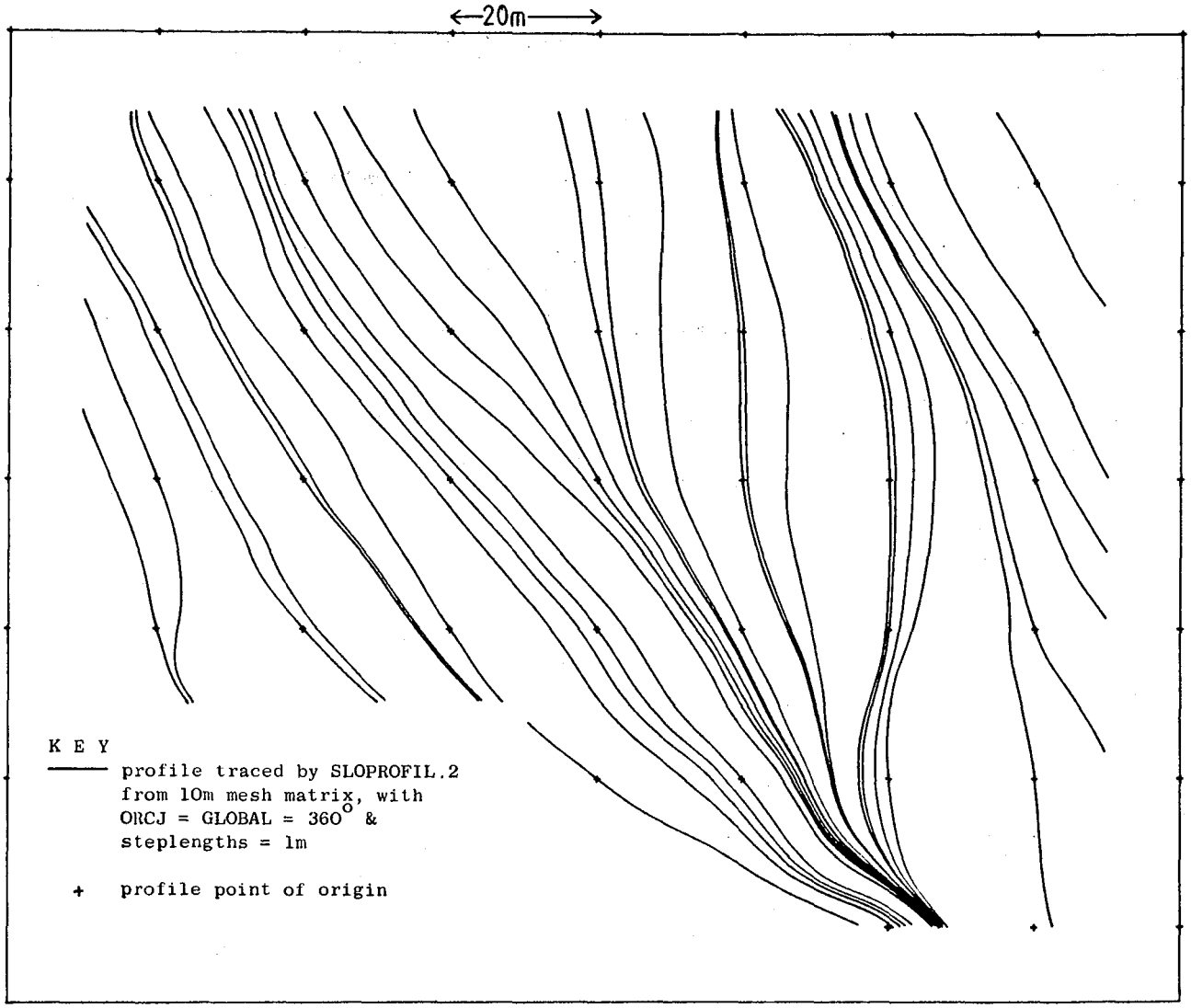


Figure 10.1 : Profiles traced from a grid pattern of points of origin in Eastergrounds hollow, Gara catchment.
Altitude is highest along the top of the map and at its lowest in the bottom right-hand corner.
Matrix surveyed by D.P.Butcher of Huddersfield Polytechnic.

The disadvantage of the unit catchment approach is that it is expensive of computer time in generating all the profiles, and requires non-automated labour also in the laying of lines along contours to count orthogonals. The most efficient method to define area drained per unit contour length would be to divide the catchment up completely into strips of land bounded by profiles, for each of which area drained per unit contour length could be defined at one or more bands extended horizontally across the strip by calculation of the area enclosed by the profiles extending upslope from the band. Since SLOPROFIL.2 gives co-ordinates and gradients of steplengths followed, surface areas rather than simply area in plan could be calculated. The difficult part would be the division of the catchment into a number of strips extending from crest to base of each slope. Profiles extended from a grid pattern of points do not define strips in the required way. A series of PSBL profiles would give the strips and would ensure that adjacent profiles were generated one after the other; however the geomorphologist would need to ensure that all slopes were reachable by profiles extended from this PSBL, by adjusting the latter until this was achieved. Paired talweg or divide profiles could possibly be used as an alternative, if the recommendations made in the previous chapter were carried out such that it could be guaranteed that paired profiles extended from these lines would ascend opposite slopes and not the talweg/divide.

It would also be interesting to investigate the following statement by Carson and Kirkby : 'If slope profiles are traced on a map ..., it is found that most points lie on profiles which terminate in major valleys, and only a few in small lateral channels which have very restricted valley development. It may therefore be useful to distinguish between a 'valley density', defined as the reciprocal of twice the mean

slope length; and the drainage density defined in the usual way' (1972, 414). The authors do not say how such map-derived orthogonals were located or whether they were allowed to curve in plan, nor do they define 'major valleys' and 'small lateral channels'. Definition of such morphometric properties directly from slopes rather than indirectly through drainage density is made possible with SLOPROFIL.2.

The approach of this research has been to consider the land surface as continuous, rather than immediately compartmentalizing it into slopes straight and curved in plan, or agonizing over the definition of a talweg. Profiles can be made to extend to the basin outlet or stop at the nearest local baselevel, depending on values of ORCJ and GLOBAL selected by the user of SLOPROFIL.2. This approach has much in common with that of the hydrologist, who needs to stress all the time the dynamic nature of the processes he is modelling : for example, the position of the stream head in an upper valley is realistically modelled by a probability function, rather than being demarcated rigidly on a map.

10.3 Implications for slope profiling

Various designs for locating points of origin of profiles were investigated : a grid pattern, points equally spaced along Young's profile sampling baseline, and points equally spaced along the talwegs and divides.

The grid scheme oversamples long slopes, which can be corrected for in analysis by giving each profile (rather than each steplength) equal weight, for example of one. Coverage of an area by profiles is excellent when a dense sample of these points of origin is used; there is some danger with sparser grids that extensions of a basin will be over- or under-sampled depending on the exact incidence of the grid. The grid

scheme does not provide the geomorphologist with an ordered spatial sequence of profiles along a slope : neighbouring grid profiles may descend opposite slopes. For a geomorphological enquiry into auto-correlation of profile attributes along slopes - for example - such a sample may not therefore be ideal. If however the goal is to generate a set of profiles that can yield unbiased estimates of any profile-based attribute of land surface form, this is a sensible choice of sampling scheme.

Profiles initiated half-way between talwegs and divides in the PSBL scheme tend to undersample divide areas unless the PSBL is taken very close to the heads of first-order valleys, in which case it tends to oversample the latter. This is a difficult option to use successfully : the geomorphologist must decide in advance what constitutes the population of slopes he wishes to study, and where the dividing line is between a talweg and a hollow. It is unlikely that he will resolve all these questions satisfactorily first time around, in which case a dense sample of computer profiles generated from his PSBL will indicate which areas have been over- or under-sampled, and modifications can be made to this PSBL accordingly. For some applications the ordered spatial sequence of profiles provided by this method is desirable.

The combination of talweg and divide locations for points of origin of profiles saves the geomorphologist the tricky step of constructing a PSBL. Talwegs and divides should be constructed from a contour map interpolated from the matrix to be used, the former by the contour crenulation method. The option is made more difficult by the fact that <u>at</u> the divide or talweg, the direction of maximum slope is often not down or up one of the two adjacent valleysides : the procedure of a fieldworker starting at such a location would be to

walk some way away from the talweg/divide and commence profiling where the valleyside slope angles became greater than those of the plunge of the talweg/divide. A method of programming such a procedure for SLOPROFIL.2 is recommended in chapter 9.

Computer-derived profiles are useful in themselves, but many geomorphologists may require more detailed topographic information than profiles from a 50 m mesh matrix (for example) are able to supply directly. The computer method is then useful for planning a field survey, in the following way. After making or getting hold of a matrix of the area of interest, the geomorphologist should generate a large grid pattern of profiles (100 or more) using values of the termination variables in SLOPROFIL.2, ORCJ (maximum local orientation change) and GLOBAL (maximum overall orientation change of profile), of 10° and 40 - 45° respectively. (These values represent an arbitrary starting position, suggested because they were the ones found successful in the more dissected Gara and Ferro catchments : when experimenting with a rugged catchment like the Netherhearth, the geomorphologist may wish to start with ORCJ = 60° and GLOBAL = 90°, as were found successful there). Statistics from point-based estimates of land surface attribute values from Evans' program G, put to work on the same altitude matrix, can be used as a yardstick to judge the representativeness (lack of bias) of surface coverage by profiles as evidenced by their summary statistics (especially those of altitude, and mean gradient). If agreement with G is not obtained, experimentation should be carried out with different values of ORCJ and GLOBAL, inspecting map coverage by profiles in addition to suggest where under- or over-sampling is occurring. When terminating variable values giving agreement with G have been found, the investigator may decrease the profile sample size until an accurate sample that he considers it feasible to measure in the

field has been determined. It may be found necessary to alter terminating variable values for the small sample if the terrain is extremely uneven in detail, as was the case in the Netherhearth.

Results from the relatively homogeneous 27 km^2 Gara catchment suggested that 20 profiles were adequate to obtain the target of agreement with G results set (at $\pm$2% of G value for at least mean altitude and mean gradient); however for the 118 km^2 Ferro catchment, complicated on a detailed scale by gulley dissection, it could not be guaranteed that 50 profiles were enough, although 100 profiles certainly were. The 1 km^2 Netherhearth catchment was similarly disturbed at a detailed scale by peat haggs registered on this 10 m mesh matrix; here 32 profiles were the minimum to yield acceptable results.

The geomorphologist may then proceed into the field armed with a map showing the paths of the profiles he is to measure. This means that no difficult decisions have to be fudged, or implications guessed at, in the field, because they will have been dealt with during the planning stage on computer when time is usually less pressing and experimentation costs less effort. Altitude matrices made from maps allow the slope profiler to undertake a sophisticated version of the pre-fieldwork map analysis that many workers (e.g. Gerrard, 1982) have described.

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APPENDICES

1a Listing of program SLOPROFIL.2

b Explanation of input required by SLOPROFIL.2

c Sample of input for SLOPROFIL.2

2a Listing of field profile data for Gara catchment

b Listing of field profile data for Netherhearth catchment

Appendix 1a Listing of program SLOPROFIL.2

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C      "SLOPROFIL.2"            USES *NAG+*GHOST
C PROGRAM TRACES MAX. GRADIENT PATHS THROUGH ALTITUDE MATRIX,STARTING AT
C POINTS PICKED IN VARIOUS WAYS OF USER'S CHOICE AND TAKING STEPS ALTERNATELY
C IN UP- & DOWN-SLOPE DIRECTIONS THEREFROM.FACILITIES BUILT IN TO TERMINATE
C EACH UP- AND DOWN-SLOPE TRACE AT LARGE LOCAL ORIENTATION CHANGE,LARGE
C DEVIATION FROM OVERALL PROFILE DIRECTION,FLAT,OR WHEN 'NHOPS' POINTS HAVE BEEN
C TRACED IN THAT DIRECTION(INCLUDING STARTING-POINT) - WHICHEVER IS SOONEST.

C REQUIREMENTS:ALTITUDE MATRIX DATA TO BE IN (F8) FORM,MAX 99 VALUES PER LINE
C IN FILE,LISTED ALONG ROWS STARTING NW CORNER;
C POINTS OUTSIDE AREA OF INTEREST TO BE DENOTED BY 0.0'S(THEREFORE NO 0.0
C ALTITUDES ALLOWED WITHIN AREA OF INTEREST).IF ALT.MAT. DATA NOT IN THIS FORM,
C RUN SUPPORTING PROGRAM 'WORDSET.2' ON MATRIX FILE FIRST.

C OUTPUT:
C 1)OPTIONAL:TABLE OF CO-ORDS,HEIGHTS,GRADTS,ORIENTS FOLLOWED FOR EACH PROFILE;
C 2)FILE LISTING GROUND SLOPE LEN'S,GRADT'S,ORIENT'S,START-POINT OF EACH
C   PROFILE,WHICH CAN BE INPUT TO ROUTINES FOR CALCULATING SUMMARY STATISTICS;
C 3)TABLE SHOWING PROFILES' LENGTHS & REASONS WHY EACH PROFILE TERMINATED AT
C   BOTH ENDS;
C 4)PLOT SHOWING  PROFILES' POSITIONS WITHIN AREA COVERED BY MATRIX, THE
C 'STARTER-POINTS' BEING MARKED WITH A '+' AND LABELLED WITH PROFILE NUMBER.

C UNIT 1:FOR INPUT OF ADDITIONAL PLOTTING MATERIAL(EG DIG CONTOURS)-OPTIONAL,
C (FLAG,X,Y TRIPLETS,SAME CO-ORD SYSTEM AS MATRIX,FLAG=1 TO END A LINE,FMT
C I1,2F8.4).
C UNIT 2:FOR OUTPUT TO ROUTINES FOR SUMMARY STATISTICS
C UNIT 4:FOR INPUT OF MATRIX OF ALTITUDES
C UNIT 5:FOR INPUT OF RUN PARAMETERS
C (SOME FIGURES TO CHECK ARE OUTPUT TO UNIT 6)
C UNIT 7:PROFILE STARTING-POINTS FILE(X,Y PAIRS,SAME CO-ORD SYSTEM AS MATRIX,
C         FORMAT(1X,2F8.4))-OPTIONAL.IF STREAM & DIVIDE OPTION BEING USED,
C         '1X' MUST BE REPLACED BY I1,=5 FOR STREAM PT'S,7 FOR DIVIDE.
C UNIT 8:MAIN PRINTED OUTPUT
C UNIT 9:PLOTTED OUTPUT

C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

      LOGICAL *1 TITLE(20)
      REAL*8  REALIN,ALT,STX,STY,X,Y,GRAD,THETAD,ANGDEG,THETA,
     1 DEG,DRAG
      COMMON/MAT/REALIN(300,300),NCOL,NROW
      COMMON/ATPT/THETAD(9999,2),X(9999,2),Y(9999,2),GRAD(9999,2),
     1 INF
      COMMON/ALINE/ANGDEG(9999,2),ALT(9999,2)
      COMMON NCOUNT,NHOPS,GR,ORCJ,GLOBAL,STEPLN,NFLG(2),IUP,
     1 NUPDOW(2)
      DIMENSION STX(5000),STY(5000),AXIS(2),AYIS(2),ANGOUT(20000),
     1 ORDOUT(20000),GSLOUT(20000),NFLARY(10000),ALTARY(20000),M(2),
     2 DLEARY(10000),NF(5000)
      DATA NDPRO/0/

C REALIN ARRAY STORES MATRIX OF HEIGHTS IN M(REAL*8).
C NCOL IS NO OF COL'S IN MATRIX,NROW NO OF ROWS.GR ITS MESH IN M.
C STX,STY ARRAYS HOLD CO-ORD'S OF PROFILE STARTING-POINTS.
C X,Y,ALT ARRAYS HOLD CO-ORD'S & CALCULATED ALTITUDES OF POINTS TRACED;
C GRAD ARRAY HOLDS VALUES FOR GRADIENT AT-A-POINT;ANGDEG,THETAD ARRAYS
C HOLD GRADIENTS AND ORIENTATIONS OF LINES BETWEEN POINTS.*
C NCOUNT:COUNTER OF NO. OF POINTS TRACED(INCREMENTED EACH TIME A CYCLE OF 1
C UPSLOPE & 1 DOWNSLOPE STEP HAS BEEN COMPLETED).
C (* ARRAYS ARE 2-D TO HOLD VALUES FOR TRACE UPSLOPE & DOWNSLOPE FOR
C EACH 'NCOUNT';'IUP' IS 1 FOR UPSLOPE,2 FOR DOWN).
C NHOPS:THE MAX NUMBER OF NCOUNT TO BE ALLOWED.ORCJ:MAX ORIENT CHANGE ALLOWED
C BETWEEN SUCCESSIVE STEPLENGTHS.GLOBAL:MAX ORIENT CHANGE ALLOWED
```

```
C BETWEEN ANY 1 STEP AND THE OVERALL PROFILE DIRECTION.
C STEPLN:THE 'MEASURED LENGTH' EXPRESSED IN MATRIX CO-ORD UNITS.
C NUPDOW:RECORDS NO.OF POINTS TRACED UPSLOPE(NUPDOW(1))& DOWNSLOPE(NUPDOW(2)).
C NFLG ARRAY:FLAG PASSED BACK FROM SUBROUTINES TO SAY WHY PROFILE ENDED.
C NFLARY:ARRAY RECORDING TERMINATING CONDITIONS FOR EVERY PROFILE.
C NPROFS:NO.OF PROFILES SUCCESSFULLY TRACED.
C GSLOUT,ANGOUT,OROUT:ARRAYS FOR OUTPUT ON UNIT 2.
C ALTARY:ARRAY OF ALTITUDES OF STARTING-POINTS.
C AXIS,AYIS,M:USED IN PLOTTING SUPPLEMENTARY MATERIAL.
C NF,INF:FOR STREAM & DIVIDE OPTION,FORMER HOLDS 5'S & 7'S FOR S OR D,LATTER
C IS USED IN PREPARATORY PART WHERE DIRECTION TO PROCEED DETERMINED.


      INF=0
      IFSND=0

C READ RUN PARAMETERS FROM UNIT 5 & RECORD ON UNIT 8
      READ(5,8)(TITLE(I),I=1,20)
    8 FORMAT(20A1)
      WRITE (8,9)(TITLE(I),I=1,20)
    9 FORMAT (1X, 'SLOPROFIL.2 ON ',20A1)

      READ(5, 29)NCOL
   29 FORMAT(I3)
      READ(5,29)NROW
      READ(5, 59)NWORD
   59 FORMAT(I2)
      WRITE (6, 69) NCOL, NROW, NWORD
   69 FORMAT(/,'NO OF COLS IS ',I3,' NO OF ROWS IS ',I3,/,
     1 'NO OF DATA VALUES/ROW IN MATRIX FILE IS ',I2)
      WRITE(8,69)NCOL,NROW,NWORD
      READ(5, 89)GR
   89 FORMAT(F6.2)
      READ(5,109)N
  109 FORMAT(I1)
      IF(N.EQ.0)CJ=0.3048
      IF(N.EQ.1)CJ=1.0
      WRITE(6,119)GR,CJ
  119 FORMAT(/,'GRID MESH IN M IS ',F6.2,/,'MULTIPLY BY ',
     1 F6.4,' TO CONVERT HEIGHTS TO METRES')
      WRITE(8,119)GR,CJ
      READ(5,18)NHOPS,ORCJ,GLOBAL,STEPLN
   18 FORMAT(I4,2F6.2,F5.3)
      STEP=STEPLN*GR
      WRITE(8,19)STEP,ORCJ,GLOBAL,NHOPS
   19 FORMAT('LENGTH BETWEEN PROFILE STATIONS CONSTANT AT ',F7.3,
     1 ' METRES',/,'PROFILE TERMINATES IF:-',/,'1)TRACE SUDDENLY',
     2 ' SWINGS THROUGH MORE THAN ',F5.1,' DEGREES,OR',/,
     3 '2)DEVIATES BY MORE THAN ',F5.1,' DEGREES FROM OVERALL',
     4' PROFILE DIRECTION,OR',/,'3)EDGE OF STUDY AREA REACHED,OR',
     5 /,'4)WHEN ',I4,' POINTS HAVE BEEN TRACED UP OR DOWN FROM',
     6 ' START,OR',/,'5)FLAT REACHED,OR',/,'6)REVERSE IN SIGN OF ',
     7 'SLOPE ANGLE',/,'7)R & DIVIDE OPTION:MEANS 1 END NOT TRACED',
     8 ' FROM')

      WRITE(6,17)ORCJ,GLOBAL,STEP
   17 FORMAT('ORCJ ',F5.1,'GLOBAL ',F5.1,'STEPLENGTH ',F7.3,'M')

C IWRITE=1 IF FULL LISTING REQUIRED.NADDIT=1 IF ADDITIONAL INFO TO BE PLOTTED.
C IPTION VALUE INFORMS PROGRAM OF PROFILE STARTING-PT OPTION REQUIRED
      READ(5,109)IWRITE
      READ(5,109)NADDIT
      READ(5,109)IPTION

```

```
C READING IN ALT.MAT. TO  REAL ARRAY
      DO 5 J = 1, NROW
      DO 15 I = 1, NCOL, NWORD
      IN = I
      NOUT = I + (NWORD - 1)
      IF(NOUT.GT.NCOL)NOUT=NCOL
      READ (4,199) (REALIN(K,J),K=IN,NOUT)
  199 FORMAT (99F8.1)
      IF (N.EQ.1)GO TO 15
      DO 255 K=IN,NOUT
      REALIN(K,J)=REALIN(K,J)*0.3048
  255 CONTINUE
   15 CONTINUE
    5 CONTINUE

      IF(IPTION.GT.1)GO TO 10
C*****STARTING OPTION 1:RANDOM VERTICES
      READ(5,169)N
  169 FORMAT(I4)
      WRITE(8,179)N
  179 FORMAT(/,'STARTING FROM ',I4,' RANDOMLY-PICKED VERTICES')
        CALL RAND(N,STX,STY)
      GO TO 20
C* * * * *

   10 IF(IPTION.GT.2)GO TO 30
C*****STARTING OPTION 2:SYSTEMATIC VERTICES
      READ(5,198)NSPACE
  198 FORMAT(I2)
      READ(5,197)IIX,IIY
  197 FORMAT(2I3)
      WRITE(8,209)NSPACE,IIX,IIY
  209 FORMAT(/,'STARTING FROM GRID PATTERN OF VERTICES,SPACING ',
     1 'EQUALS ',I2,/,'TOP LEFT-HAND VERTEX ',2I3)
      CALL YSTEM(NSPACE,STX,STY,N,IIX,IIY)
      GO TO 20
C* * * * *

C*****STARTING OPTION 3:DIGITISED CO-ORDINATES
   30 READ(5,169)N
C IFSND=1 IF START POINTS ARE STREAM & DIVIDE
      READ(5,109)IFSND
      IF(IFSND.EQ.1)GO TO 120
      WRITE(8,229)N
  229 FORMAT(/,'STARTING FROM ',I4,' DIGITIZED CO-ORDINATES')
      DO 25 J=1,N
      READ(7,239)STX(J),STY(J)
  239 FORMAT(1X,2F8.4)
   25 CONTINUE
      GO TO 20

C STREAM & DIVIDE CASE:EACH START POINT GENERATES 1 OR 2 START POINTS 'AMULT'
C STEPLENGTHS AWAY FROM ITSELF IN THE DIRECTION ORTHOG TO PLUNGE OF TALWEG OR
C DIVIDE
  120 READ(5,228)AMULT,IPAIR
  228 FORMAT(F5.2,I1)
      IF(IPAIR.EQ.2)WRITE(8,227)N,AMULT
  227 FORMAT('R & DIVIDE,SO ',I4,' PAIRED PROFILES.EACH PROFILE ',
     1 'STARTS ',F5.2,' STEPLENGTHS FROM ORIGINAL R OR DI POINT')
      IF(IPAIR.EQ.1)WRITE(8,226)N,AMULT
  226 FORMAT('R & DIVIDE,SO ',I4,' PROFILES TO START ',F5.2,
     1 ' STEPLENGTHS FROM ORIGINAL R OR DI POINT')
      IF(IPAIR.EQ.2)N=N*2
      INF=1
```

```
      J=1
  130 READ(7,339)NF(J),STX(J),STY(J)
  339 FORMAT(I1,2F8.4)
C PREPARE TO TRACE UPSLOPE 1 STEP FROM START-POINT INPUT
      X(1,1)=STX(J)
      Y(1,1)=STY(J)
      X(1,2)=STX(J)
      Y(1,2)=STY(J)
      IUP=1
      NCOUNT=1
      NFLG(1)=0
      NFLG(2)=0
      CALL TRACE
C IF START-POINT NOT TOO NEAR EDGE OF STUDY AREA TO ALLOW SURFACE-FITTING...
      IF(NFLG(1).EQ.0)GO TO 340
      IF(IPAIR.EQ.2)N=N-2
      IF(IPAIR.EQ.1)N=N-1
      IF(J.LE.N)GO TO 130
      IF(J.GT.N)GO TO 355

C THETAD IS BEARING AT 90 DEGREES TO THE 1 OR 2 YOU WANT
C CREATE A 2ND START POINT IF PAIRED OPTION CHOSEN...
  340 IF(IPAIR.EQ.1)GO TO 341
      STX(J+1)=STX(J)+DCOS(THETAD(1,1)+3.14159/2.0)*STEPLN*AMULT
      STY(J+1)=STY(J)+DSIN(THETAD(1,1)+3.14159/2.0)*STEPLN*AMULT
      NF(J+1)=NF(J)
C REDEFINE ST PT YOU READ IN
  341 STX(J)=STX(J)+DCOS(THETAD(1,1)-3.14159/2.0)*STEPLN*AMULT
      STY(J)=STY(J)+DSIN(THETAD(1,1)-3.14159/2.0)*STEPLN*AMULT
      IF(IPAIR.EQ.2)J=J+2
      IF(IPAIR.EQ.1)J=J+1
      IF(J.LE.N)GO TO 130

  355 INF=0

C* * * * *

C SET-UP FOR PLOT (*GHOST)
   20 CALL PAPER(1)
      ROW = FLOAT(NROW)
      COL = FLOAT(NCOL)
      CALL PSPACE(0.15, 2.55, 0.15, 2.55)
      CALL CSPACE(0.0, 3.0, 0.0, 3.0)
      IF(NCOL.LE.NROW)CALL MAP(1.0, ROW, ROW, 1.0)
      IF(NCOL.GT.NROW)CALL MAP(1.0,COL,COL,1.0)
      CALL WINDOW(1.0, COL, ROW, 1.0)
      CALL BORDER
      CALL CTRMAG(20)

C TITLES FOR TABLE
      IF(IWRITE.EQ.0)WRITE(8,498)
      IF(IWRITE.EQ.1)WRITE (8,149)
  149 FORMAT('-----------------------------------',
     1'-----------------------------',/,
     2 3X,'CO-ORD S      CALC.   1ST VERT.',1X,'GRADT.',
     3 ' ORIENT.   REASON FOR',/,17X,'ALT.(M)',5X,'DERIV.',20X,
     4'TERMINATION')

C LOOP COMPLETED ONCE PER PROFILE
      DO 35 I=1,N
      WRITE(6,169)I

C START TO TRACE PROFILE.IUP IS 1 FOR ASCEND 1ST STEP,COUNTER TO 1,
C TERMINATING DIAGNOSERS TO 0
```

```
257          IUP=1
258          NCOUNT=1
259          NFLG(1)=0
260          NFLG(2)=0
261          NUPDOW(1)=1
262          NUPDOW(2)=1
263    C STREAM & DIVIDE...
264          IF(IFSND.EQ.0)GO TO 280
265          IF(NF(I).EQ.5)NFLG(2)=7
266          IF(NF(I).EQ.7)IUP=2
267          IF(NF(I).EQ.7)NFLG(1)=7
268
269      280 X(1,1)=STX(I)
270          X(1,2)=STX(I)
271          Y(1,1)=STY(I)
272          Y(1,2)=STY(I)
273          STEX=STX(I)
274          STEY=STY(I)
275          IX=IFIX(STEX)
276          IY=IFIX(STEY)
277
278      110 CALL TRACE
279
280    C WRITING & PLOTTING - UPSLOPE FIRST
281          IUP=1
282    C (IF START-POINT TOO CLOSE TO EDGE OF STUDY AREA TO ALLOW SURFACE-FITTING,
283    C GO TO END OF 'LOOP COMPLETED ONCE PER PROFILE')
284          IF(NUPDOW(1).EQ.0.OR.NUPDOW(2).EQ.0)GO TO 35
285          IF(IWRITE.EQ.1)WRITE(8,289)
286      289 FORMAT('-------------------------------------------',
287         1 '--------------------')
288
289    C RECORDING TERMINATING CONDITIONS(NFLAG'S)FOR EACH PROFILE
290          NFLARY(NPROFS*2 - 1)=NFLG(1)
291          NFLARY(NPROFS*2)=NFLG(2)
292
293    C BELOW IS EXECUTED ONCE ON UPSLOPE & ONCE ON DOWNSLOPE TRACE FOR EACH PROFILE
294
295    C IF 1 POINT ONLY WAS TRACED(IE DIDN'T GET BEYOND START-POINT)
296      660 IF(NUPDOW(IUP).NE.1)GO TO 440
297          IF(IUP.EQ.2.AND.NUPDOW(2).EQ.1)GO TO 350
298          GO TO 450
299
300    C CRESTAL POINT...
301      440 IF(IUP.EQ.1.AND.IWRITE.EQ.1)WRITE(8,709)X(NUPDOW(1),1),
302         1 Y(NUPDOW(1),1),ALT(NUPDOW(1),1),GRAD(NUPDOW(1),1),
303         2 NFLG(1)
304      709 FORMAT(F6.2,1X,F6.2,3X,F7.2,1X,F7.3,21X,I1)
305
306    C PLOT (UPSLOPE OR DOWNSLOPE) PATH OF PROFILE ON MAP
307    C PLOTS STARTING-POINT WITH '+'
308          CALL PLOTNC(STEX,STEY , 43)
309    C LEAVE OUT LINE BELOW IF WANT NUMBERING OF PROFILES ON PLOT
310          GO TO 112
311          IF (I .GT. 9) GO TO 100
312          CALL PLOTNC(STEX + 1.0, STEY, I)
313          GO TO 112
314      100 IF(I .GT.99)GO TO 111
315          NUM = I / 10
316          MUM = I - NUM * 10
317          CALL PLOTNC(STEX + 1.0, STEY, NUM)
318          CALL PLOTNC(STEX + 2.0, STEY, MUM)
319          GO TO 112
320      111 MUMMER= I /100
```

```
321          NUM=( I -MUMMER*100)/10
322          MUM=I -MUMMER*100-NUM*10
323          CALL PLOTNC(STEX  +1.0,STEY  ,MUMMER)
324          CALL PLOTNC(STEX  +2.0,STEY  ,NUM)
325          CALL PLOTNC(STEX  +3.0,STEY  ,MUM)
326      112 CALL POSITN(STEX,STEY)
327          NPD=NUPDOW(IUP)
328          DO 555 J=2,NPD
329          STAR4X=X(J,IUP)
330          STAR4Y=Y(J,IUP)
331          CALL JOIN(STAR4X,STAR4Y)
332      555 CONTINUE
333
334
335          DO 145 K=2,NPD
336    C BECAUSE ARRAYS HOLDING PROF DETAILS WORK OUTWARDS UPSLOPE & DOWNSLOPE FROM
337    C START-POINT...
338          IF(IUP.EQ.1)J=NPD+1-K
339          IF(IUP.EQ.2)J=K
340
341    CHANGING ORIENT'S ACCORDING TO 'SLOPROFIL.2'S COMPASS' TO CONVENTIONAL BEARINGS
342          IF(IUP.EQ.1)THETA=-THETAD(J,IUP)
343          IF(IUP.EQ.2)THETA=180.0-THETAD(J-1,IUP)
344          IF(THETA.LT.0.0)THETA=THETA+360.0
345
346          IF(IUP.EQ.1)DEG=ANGDEG(J,IUP)
347          IF(IUP.EQ.2)DEG=-ANGDEG(J-1,IUP)
348          IF(IWRITE.EQ.1)WRITE(8,279)DEG,THETA
349      279 FORMAT(33X,F7.3,1X,F8.3)
350
351    C PREPARE ARRAYS FOR OUTPUT ON UNIT 2
352          IF(IUP.EQ.1)ANGOUT(K-1)=DEG
353          IF(IUP.EQ.2)ANGOUT(NUPDOW(1)+K-2)=DEG
354          IF(IUP.EQ.1)OROUT(K-1)=THETA
355          IF(IUP.EQ.2)OROUT(NUPDOW(1)+K-2)=THETA
356
357    C GROUND SLOPE,AS OPPOSED TO HORIZONTAL(CONSTANT),LENGTH REQUIRED
358          S=STEP/DCOS(DEG*3.14159/180.0)
359          IF(IUP.EQ.1)GSLOUT(K-1)=S
360          IF(IUP.EQ.2)GSLOUT(NUPDOW(1)+K-2)=S
361
362          IF(K.EQ.NPD)GO TO 145
363          IF(IUP.EQ.1)DRAG=GRAD(J,IUP)
364          IF(IUP.EQ.2)DRAG=-GRAD(J,IUP)
365          IF(IWRITE.EQ.1)WRITE(8,299)X(J,IUP),Y(J,IUP),ALT(J,IUP),DRAG
366      299 FORMAT(F6.2,1X,F6.2,3X,F7.2,1X,F7.3)
367      145 CONTINUE
368
369      450 IF(IUP.EQ.2)GO TO 300
370          ALTARY(I)=ALT(1,1)
371          IF(NFLG(1).EQ.7)ALTARY(I)=ALT(1,2)
372          IF(IWRITE.NE.1)GO TO 451
373          IF(IPTION.EQ.1.OR.IPTION.EQ.2)WRITE(8,589)X(1,1),
374         1 Y(1,1),ALT(1,1),GRAD(1,1),I,REALIN(IX,IY)
375      589 FORMAT(F6.2,1X,F6.2,3X,F7.2,1X,F7.3,21X,'START-PT ',I3,
376         1 '(ALT.',F7.2,' M)')
377          IF(IPTION.EQ.3)WRITE(8,489)X(1,1),Y(1,1),
378         1 ALT(1,1),GRAD(1,1),I
379      489 FORMAT(F6.2,1X,F6.2,3X,F7.2,1X,F7.3,21X,'START-PT ',I3)
380
381    C DOWNSLOPE....
382      451 IF(NUPDOW(1).EQ.0)NUPDOW(1)=1
383          IUP=2
384          GO TO 660
```

```
  300 DRAG=-GRAD(NPD,IUP)
      IF(IWRITE.EQ.1)WRITE(8,709)X(NPD,IUP),Y(NPD,IUP),
     1 ALT(NPD,IUP),DRAG,NFLG(IUP)

C WRITE TO FILE ON UNIT 2 THAT CAN BE USED TO CALC SUMMARY STAT'S FOR PROF'S
  350 NCO=NUPDOW(1)+ NUPDOW(2) - 2
      IF(NCO.LT.3)GO TO 35
C COUNTS NO.OF PROFILES
      NOPRO=NOPRO+1

      WHOLE=NCO*STEP
      OLEARY(NPROFS)=WHOLE
C(HOW PROF'S ENDED...)
      IF(IWRITE.EQ.0)WRITE(8,497)I,NFLG(1),NFLG(2),WHOLE
      WRITE(2,909)I
  909 FORMAT(1X,I3)
      WRITE(2,919)NCO
  919 FORMAT(I4)
      WRITE(2,929)
  929 FORMAT('1')
      WRITE(2,939)(GSLOUT(II),II=1,NCO)
  939 FORMAT(13F6.2)
      WRITE(2,949)(ANGOUT(II),II=1,NCO)
  949 FORMAT(16F5.1)
      WRITE(2,949)(OROUT(II),II=1,NCO)
      WRITE(2,959)
  959 FORMAT('0')
      WRITE(2,959)
      WRITE(2,969)NUPDOW(1),STX(I),STY(I),ALTARY(I)
  969 FORMAT(I4,2F8.4,F7.2)

   35 CONTINUE

C SUMMARIZES WHY PROFILES TERMINATED
      IF(IWRITE.EQ.0)GO TO 496
      IF(IWRITE.EQ.1)WRITE(8,19)STEP,DRCJ,GLOBAL,NHOPS
      WRITE(8,498)
  498 FORMAT('PROFILE NO.',2X,'UPSL.END',2X,'DOWNSL.END',2X,
     1 'HORIZ.LENGTH')
      DO 495 I=1,NOPRO
      NFIR=I*2 - 1
      NSEC=I*2
      WRITE(8,497)I,NFLARY(NFIR),NFLARY(NSEC),OLEARY(I)
  497 FORMAT(I4,12X,I1,9X,I1,12X,F9.1)
  495 CONTINUE
  496 CONTINUE

C PLOTS RELEVANT ADDITIONAL INFO IF REQUIRED(EG DIG CONTOURS)
      IF(NADDIT.EQ.0)GO TO 460
      CALL BROKEN(2,15,2,15)
  700 READ(1,499,END=460)M(1),AXIS(1),AYIS(1)
  499 FORMAT(I1,2F8.4)
      IF(AXIS(1).GT.NCOL.OR.AYIS(1).GT.NROW)GO TO 700
      CALL POSITN(AXIS(1),AYIS(1))
  600 READ(1,499,END=460)M(2),AXIS(2),AYIS(2)
      IF(AXIS(2).GT.NCOL.OR.AYIS(2).GT.NROW)M(1)=1
      IF(M(1).NE.1)CALL JOIN(AXIS(2),AYIS(2))
      IF(M(1).EQ.1)GO TO 700
      AXIS(1)=AXIS(2)
      AYIS(1)=AYIS(2)
      M(1)=M(2)
      GO TO 600

  460 CALL GREND
```

```
      WRITE(6,609)NOPRO
  609 FORMAT(///,'NO.OF PROFILES HAVING >3 STEPLENGTHS IS ',I5)
      STOP
      END

C-----------------------------------------------------------------

      SUBROUTINE RAND( NRAND,STX,STY)

C RANDOM VERTEX GENERATION

      REAL*8 REALIN,STX,STY
      COMMON/MAT/REALIN(300,300),NCOL,NROW
      DIMENSION STX(NRAND),STY(NRAND)

C RANDOM NUMBER GENERATION INITIALIZATION (*NAG)
      CALL G05CBF(0)

      COL=FLOAT(NCOL)
      ROW=FLOAT(NROW)
      K=0
C (X,Y) ARE CO-ORD'S OF PT RANDOMLY PICKED WITHIN ALT.MAT.
   10 X = G05CAF(R1) * COL
      Y = G05CAF(R2) * ROW

C ORIGIN OF ALTITUDE MATRIX IS (1,1).
C CO-ORD'S ARE MADE INTEGER TO BE VERTICES .
C ZERO ALTITUDE POINTS ARE OUTSIDE AREA OF INTEREST
      IF (X .LT. 1.0) GO TO 10
      IF (Y .LT. 1.0) GO TO 10
      JX = IFIX(X)
      JY = IFIX(Y)
      IF (REALIN(JX,JY) .EQ. 0.0) GO TO 10
      K=K+1

      STX(K)=DFLOAT(JX)
      STY(K)=DFLOAT(JY)

      IF(K.LT.NRAND)GO TO 10

      RETURN
      END

C-----------------------------------------------------------------

      SUBROUTINE YSTEM(NSPACE,STX,STY,K,IX,IY)

C SYSTEMATIC VERTEX GENERATION

      REAL*8  REALIN,STX,STY
      COMMON/MAT/REALIN(300,300),NCOL,NROW
      DIMENSION STX(5000),STY(5000)

      K=0
      DO 5 J=IY,NROW,NSPACE
      DO 15 I=1,NCOL,NSPACE
      IF(J.EQ.IY.AND.I.LT.IX)GO TO 15
      IF(REALIN(I,J).EQ.0.0)GO TO 15
      K=K+1
      STX(K)=DFLOAT(I)
      STY(K)=DFLOAT(J)
   15 CONTINUE
    5 CONTINUE
```

```
      RETURN
      END

C-----------------------------------------------------------------------

      SUBROUTINE TRACE
C TAKES START-PT CO-ORD'S INPUT AND ARRANGES TRACE ACROSS RELEVANT UNIT SQUARE
C BY CALLS TO QUAD,JNJFIT,ASPGDT.CONTINUES WITH SUCCESSIVE UNIT SQUARES THAT
C TRACE MUST TRAVERSE,UNTIL PROFILE TERMINATION AT BOTH ENDS

      REAL *8 REALIN,ALT,X,Y,GRAD,THETAD,A1,B1,
     1 C1,D1,E1,F1,H,RX,RY,
     2 A,B,C,D,E,F,DEE,EEE,ANGDEG
      COMMON/MAT/REALIN(300,300),NCOL,NROW
      COMMON/ATPT/THETAD(9999,2),X(9999,2),Y(9999,2),GRAD(9999,2),
     1 INF
      COMMON/ALINE/ANGDEG(9999,2),ALT(9999,2)
      COMMON/DER/DEE,EEE,RX(2),RY(2)
      COMMON/COE/A1(4),B1(4),C1(4),D1(4),E1(4),F1(4)
      COMMON NCOUNT,NHOPS,GR,ORCJ,GLOBAL,STEPLN,NFLG(2),IUP,
     1 NUPDOW(2)
      DIMENSION H(9)

C FIT NEW SURFACE : FIRST, CALC COEFF'S OF 4 QUAD FITS

  900 STAR4X=X(NCOUNT,IUP)
      STAR4Y=Y(NCOUNT,IUP)
      IX=IFIX(STAR4X)
      IY=IFIX(STAR4Y)
      RELX=FLOAT(IX)
      RELY=FLOAT(IY)

C RX,RY ARE CO-ORD'S OF PT RELATIVE TO UPPER LH CORNER OF UNIT SQUARE
C (IE 0< OR = RX < OR = 1,DITTO RY)
      RX(IUP)=X(NCOUNT,IUP)-RELX
      RY(IUP)=Y(NCOUNT,IUP)-RELY
C INITIALLY TRACING UP- & DOWN-SLOPE FROM SAME START-POINT...
      IF(NCOUNT.EQ.1.AND.IUP.EQ.1)RX(2)=RX(1)
      IF(NCOUNT.EQ.1.AND.IUP.EQ.1)RY(2)=RY(1)
C IF-EG-INPUT CO-ORD'S ARE FOR VERTEX SO THERE ARE 4 POSSIBLE
C UNIT SQUARES FOR TRACE TO CONTINUE IN,THE DIRECTION OF DERIVATIVE WILL BE
C DETERMINED BY FITTING BOTTOM RH SQUARE HERE & SUBSTITUTING.NEXT 'PROF.STATION'
C THEREBY DEFINED WILL ENABLE PROG ON RETURN TO HERE TO FIT CORRECT SQUARE
C FOR PROFILE FURTHER CONTINUATION IF BOTTOM RH WASN'T.
      IAX=IX-1
      IDX=IX+2
      IAY=IY-1
      IDY=IY+2

C IF AREA OF MATRIX POINTS UNDER INVESTIGATION GOES OUTSIDE
C MATRIX OR AREA OF INTEREST,TERMINATE PROFILE AT THAT END
      IF(IAX.LT.1)GO TO 10
      IF(IDX.GT.NCOL)GO TO 10
      IF(IAY.LT.1)GO TO 10
      IF(IDY.GT.NROW)GO TO 10
      DO 5 J=IAY,IDY
      DO 5 I=IAX,IDX
      IF(REALIN(I,J).EQ.0.0)GO TO 10
    5 CONTINUE

C FIT 4 QUADRATIC SURFACES THAT WILL BE NEEDED FOR JANCAITIS AND JUNKINS FIT
      DO 25 NQUS=1,4
C  NUMBERING IS ALONG ROWS L-R,IE 1,2 NEXT ROW 3,4
      IF(NQUS.LT.3)JCOUNT=IAY
```

```
      IF(NQUS.GT.2)JCOUNT=IAY+1
      IF(NQUS.EQ.1.OR.NQUS.EQ.3)ICOUNT=IAX
      IF(NQUS.EQ.2.OR.NQUS.EQ.4)ICOUNT=IAX+1
C EACH QUADRATIC FIT HAS 9 HEIGHT MEMBERS,K=1 TO 9
      K=1
      DO 35 J=1,3
      III=ICOUNT
      DO 45 I=1,3
      H(K)=REALIN(III,JCOUNT)
      K=K+1
      III=III+1
   45 CONTINUE
      JCOUNT=JCOUNT + 1
   35 CONTINUE
      CALL QUAD(A,B,C,D,E,F,H)
C STORE COEFFICIENTS OF QUAD FITS FOR  LATER USE IN J & J FIT
      A1(NQUS)=A
      B1(NQUS)=B
      C1(NQUS)=C
      D1(NQUS)=D
      E1(NQUS)=E
      F1(NQUS)=F
   25 CONTINUE

C FITTING NEW SURFACE : SECOND, FIT THE 'FINAL' SQUARE FROM THE 4 OVERLAPPING
C QUADRATICS

      CALL JNJFIT
      IF(NFLG(IUP).GT.0)GO TO 565
      CALL ASPGDT
      GO TO 590

C LOOP BELOW REPEATED UNTIL TRACE HAS REACHED AN EDGE OF UNIT SQUARE(IE CARRY
C ON TRACING ACROSS SURFACE ALREADY FITTED & STORED IN SUBROUTINE 'JNJFIT')

   20 CALL DERIV
      IF(NFLG(IUP).GT.0)GO TO 565
      CALL ASPGDT
      GO TO 590
  565 CALL FINISH

  590 IF(NFLG(1).GT.0.AND.NFLG(2).GT.0)RETURN
C CASE WHERE INITIAL POINT OF STREAM OR DIVIDE PROFILE BEING DEFINED...
      IF(INF.EQ.1)RETURN

C DECIDE WHETHER TRACE BEING CONTINUED WITH HAS OVERSTEPPED THIS UNIT SQUARE
  140 IF(RX(IUP).GT.1.0.OR.RX(IUP).LT.0.0)GO TO 900
      IF(RY(IUP).GT.1.0.OR.RY(IUP).LT.0.0)GO TO 900
      GO TO 20

C CASE WHERE EDGE OF STUDY AREA REACHED
   10 NFLG(IUP)=3
      NUPDOW(IUP)=NCOUNT - 1
      IF(NFLG(1).GT.0.AND.NFLG(2).GT.0)RETURN
      IF(NCOUNT.EQ.1)RETURN
      CALL FINISH
      GO TO 140

      END

C-----------------------------------------------------------

      SUBROUTINE FINISH

```

```
641     C DETERMINES INCREMENTATION OF COUNTERS WHEN 1 END OF PROFILE HAS TERMINATED
642
643           COMMON NCOUNT,NHOPS,GR,ORCJ,GLOBAL,STEPLN,NFLG(2),IUP,
644          1 NUPDOW(2)
645
646           IF(IUP.EQ.1)GO TO 10
647           IUP=1
648           NCOUNT=NCOUNT+1
649           RETURN
650
651        10 IUP=2
652           RETURN
653           END
654
655     C-----------------------------------------------------------------------
656
657           SUBROUTINE ASPGDT
658
659     C CALCULATES SLOPE IN DEGREES BELOW HORISONTAL(IF IUP=2 FOR DESCEND)OR ABOVE IT
660     C (IF IUP=1 FOR ASCEND),AND ASPECT-ALTHO' NB 0 DEGREES HERE IS REALLY S AND
661     C ANGLES INCREASE IN ANTICLOCKWISE DIRECTION(BECAUSE Y INCREASES DOWNWARD,
662     C MEANING "SLOPROFIL.2'S COMPASS" NEEDS TO BE LIKE AN ORDINARY ONE SEEN IN A
663     C MIRROR HELD PARALLEL TO E-W AXIS).BEARINGS WILL THEREFORE
664     C BE MODIFIED BEFORE PRINTOUT (DONE IN MAIN PROGRAM).
665     C ASPECT & GRADIENT CALCULATION BASED ON M.YOUNG,1978
666
667           COMMON/ATPT/THETAD(9999,2),X(9999,2),Y(9999,2),GRAD(9999,2),
668          1 INF
669           COMMON/DER/D,E,RX(2),RY(2)
670           COMMON NCOUNT,NHOPS,GR,ORCJ,GLOBAL,STEPLN,NFLG(2),IUP,
671          1 NUPDOW(2)
672           REAL *8 D,E,SLOPR,THETAR,XUP,XDO,YUP,YDO,
673          1 DX,DY,X,Y,GRAD,THETAD,RX,RY
674
675     C PROVISION FOR FLATS
676           IF(DABS(D)+DABS(E).GT.0.0)GO TO 800
677           GRAD(NCOUNT,IUP)=0.0
678           NUPDOW(IUP)=NCOUNT
679           NFLG(IUP)=5
680           CALL FINISH
681           RETURN
682
683       800 THETAR=DATAN2(E,D)
684     C DIVIDE BY GR SO OPP & ADJACENT SIDES IN M
685           SLOPR=(D*DCOS(THETAR) + E*DSIN(THETAR))/GR
686           IF(IUP.EQ.2)GO TO 10
687     C THE UPSLOPE CASE
688           IF(SLOPR.LT.0.0)GO TO 20
689           GO TO 30
690
691     C THE DOWNSLOPE CASE
692        10 IF(SLOPR.LT.0.0)GO TO 30
693
694     C SWAP TO OPPOSITE QUADRANT IF NECESSARY
695        20 SLOPR=-SLOPR
696           THETAR=THETAR+3.14159
697
698        30 SLOPR=DATAN(SLOPR)
699           GRAD(NCOUNT,IUP)=SLOPR*57.29578
700
701     C REMEMBER:THETAD(NCOUNT,IUP) IS TO BE ORIENT OF NEXT STEP TRACED,IE COMING
702     C AFTER PT X(NCOUNT,IUP),Y(NCOUNT,IUP)
703           THETAD(NCOUNT,IUP)=90.0-THETAR*57.29578
704           IF(THETAD(NCOUNT,IUP).LT.0.0)THETAD(NCOUNT,IUP)=
```

```
     1 THETAD(NCOUNT,IUP)+ 360.0
C STREAM & DIVIDE INITIATION...
      IF(INF.EQ.1)THETAD(1,1)=THETAR

      IF(NCOUNT.EQ.1)GO TO 590
C'LARGE ORIENTATION CHANGE'(TERMINATING CONDITIONS 1 & 2)
C 2:-
      IF(IUP.EQ.2)GO TO 581
      YUP=Y(NCOUNT,1)
      XUP=X(NCOUNT,1)
      IF(NFLG(2).EQ.0)YDO=Y(NCOUNT-1,2)
      IF(NFLG(2).EQ.0)XDO=X(NCOUNT-1,2)
      IF(NFLG(2).GT.0)YDO=Y(NUPDOW(2),2)
      IF(NFLG(2).GT.0)XDO=X(NUPDOW(2),2)
      GO TO 583

  581 YDO=Y(NCOUNT,2)
      XDO=X(NCOUNT,2)
      IF(NFLG(1).EQ.0)YUP=Y(NCOUNT,1)
      IF(NFLG(1).EQ.0)XUP=X(NCOUNT,1)
      IF(NFLG(1).GT.0)YUP=Y(NUPDOW(1),1)
      IF(NFLG(1).GT.0)XUP=X(NUPDOW(1),1)

C EXPRESS ORIENT OF WHOLE PROFILE INITIALLY IN UPSLOPE-WARDS DIRECTION
  583 ALLORI=DATAN2((YUP-YDO),(XUP-XDO))
      IF(IUP.EQ.2)ALLORI=ALLORI+3.14159
      ALLORI=90.0 - ALLORI*57.29578
      IF(ALLORI.LT.0.0)ALLORI=ALLORI+360.0
      ARGE=THETAD(NCOUNT,IUP)-ALLORI
      IF(ABS(ARGE).LT.GLOBAL)GO TO 490
      NFLG(IUP)=2
      NUPDOW(IUP)=NCOUNT
      CALL FINISH
      RETURN

C 1:-
  490 ARGE=THETAD(NCOUNT-1,IUP)-THETAD(NCOUNT,IUP)
      IF(ABS(ARGE).LT.ORCJ)GO TO 580
      NFLG(IUP)=1
      NUPDOW(IUP)=NCOUNT
      CALL FINISH
      RETURN

  580 IF(NCOUNT.LT.NHOPS)GO TO 590
      NFLG(IUP)=4
      NUPDOW(IUP)=NCOUNT
      CALL FINISH
      RETURN

C HOW MUCH DO X AND Y CO-ORD'S CHANGE OVER 'STEP' THAT HAS BEEN DEFINED BUT
C NOT YET TAKEN,FROM X&Y(NCOUNT,IUP) TO X&Y(NCOUNT+1,IUP)
  590 DX=DCOS(THETAR)*STEPLN
      DY=DSIN(THETAR)*STEPLN
      X(NCOUNT+1,IUP)=X(NCOUNT,IUP)+DX
      Y(NCOUNT+1,IUP)=Y(NCOUNT,IUP)+DY
      RX(IUP)=RX(IUP)+DX
      RY(IUP)=RY(IUP)+DY

C INCREMENT NCOUNT IF HAVE TRACED UP & DOWNSLOPE AN EQUAL NO('NCOUNT')OF TIMES
C OR ARE EXEMPTED FROM PROCEDING IN 1 OR OTHER DIRECTION
      IF(IUP.EQ.2.OR.NFLG(2).GT.0)NCOUNT=
     1 NCOUNT+1

C CHANGE TO DOWNSLOPE/UPSLOPE IF PERMISSIBLE
```

```
      IF(IUP.EQ.1.AND.NFLG(2).EQ.0)GO TO 491
      IF(IUP.EQ.2.AND.NFLG(1).GT.0)GO TO 491
      IUP=1
      RETURN

  491 IUP=2
      RETURN
      END

C-----------------------------------------------------------

      SUBROUTINE QUAD(A,B,C,D,E,F,H)

C 'PRELIMINARY'FIT TO 3 X 3 POINTS

C SUBROUTINE CALCULATES COEFFICIENTS A TO F FOR QUADRATIC FIT TO 9 HEIGHTS
C FOLLOWING MARGARET YOUNG(1978).HEIGHTS NUMBERED ALONG ROWS STARTING
C TOP LH CORNER;GRID SPACING(GR) IN MATRIX CO-ORD UNITS.
C SIGNS OF C & E ARE CHANGED BECAUSE Y INCREASES DOWNWARD IN THIS PROGRAM

      REAL *8 H,A,B,C,D,E,F
      DIMENSION H(9)
      GR=1.0
      GR2=GR*GR
      A=(H(1)+H(3)-2.0*H(2)+H(4)+H(6)-2.0*H(5)+H(7)+H(9)-2.0*H(8))/
     1 (6.0*GR2)
      B=(H(1)+H(2)-2.0*H(4)+H(3)+H(7)-2.0*H(5)+H(8)+H(9)-2.0*H(6))/
     1 (6.0*GR2)
      C=-(-H(1)+H(3)+H(7)-H(9))/(4.0*GR2)
      D=(-H(1)+H(3)-H(4)+H(6)-H(7)+H(9))/(6.0*GR)
      E=-(H(1)-H(8)+H(3)-H(7)+H(2)-H(9))/(6.0*GR)
      F=(-H(1)+2.0*H(2)-H(3)+2.0*H(4)+5.0*H(5)+2.0*H(6)-H(7)+2.0*H(8)
     1 -H(9))/9.0
      RETURN
      END
C-----------------------------------------------------------------------

      SUBROUTINE JNJFIT

C (1)FITS A SURFACE TO MIDDLE UNIT SQUARE COVERED BY 4 OVERLAPPING (QUADRATIC)
C PRELIMINARIES HAVING CENTROIDS AT EACH OF THE CORNERS OF THE SQUARE -
C USING JANCAITIS & JUNKINS' (1973) WEIGHTING FUNCTION WHICH ENSURES AGREEMENT
C BETWEEN ADJACENT FINAL SURFACES IN VALUE AND 1ST PARTIAL DERIVATIVES.
C (2)CALCULATES CONSTANT TERMS DEE & EEE USED IN DETERMINATION OF SLOPE VECTOR,
C USING ROVING CO-ORD SYSTEM WITHIN UNIT SQUARE SUCH THAT X(NCOUNT,IUP),
C Y(NCOUNT,IUP) IS ALWAYS ORIGIN.
C (3)SUBSTITUTES IN TO (1) TO FIND HEIGHT AT X(NCOUNT,IUP),Y(NCOUNT,IUP).
C** SUBSCRIPT 1 ALWAYS FOR UPPER LH CORNER,2 UPPER RH,3 LOWER LH,4 LOWER RH **
C   IUP 1 FOR UPSLOPE,2 FOR DOWN

      COMMON/ALINE/ANGDEG(9999,2),ALT(9999,2)
      COMMON/DER/DEE,EEE,RX(2),RY(2)
      COMMON/COE/A(4),B(4),C(4),D(4),E(4),F(4)
      COMMON NCOUNT,NHOFS,GR,ORCJ,GLOBAL,STEPLN,NFLG(2),IUP,
     1 NUPDOW(2)
      REAL *8 A,B,C,D,E,F,DEE,EEE,RX,RY,ALT,P,Q,DIFFA,STEP,
     1 ANGDEG,CONS(2),XCOEF(2),YCOEF(2),XSQ(2),XY(2),
     2 YSQ(2),XCU(2),XSQY(2),XYSQ(2),YCU(2),XFO(2),XCUY(2),
     3 XSQYSQ(2),XYCU(2),YFO(2),XFI(2),XFOY(2),
     4 XCUYSQ(2),XSQYCU(2),XYFO(2),YFI(2),XFOYSQ(2),XCUYCU(2),
     5 XSQYFO(2),XFIYSQ(2),XFOYCU(2),XCUYFO(2),
     4 XSQYFI(2),XFIYCU(2),XFOYFO(2),XCUYFI(2)

C MAIN ENTRY CALCULATES JNJFIT FOR UNIT SQUARE WHOSE 4 A'S,B'S,C'S,D'S,E'S &
```

```
833     C F'S ARE INPUT
834
835           STEP=STEPLN*GR
836
837     C (1) WORKING OUT COEFFICIENTS OF J&J FIT
838
839           CONS(IUP)=F(1)
840
841           XCOEF(IUP)=D(1)
842
843           YCOEF(IUP)=E(1)
844
845           XSQ(IUP)=A(1) - 3*F(1) + 3*A(2) - 3*D(2) + 3*F(2)
846
847           XY(IUP)=C(1)
848
849           YSQ(IUP)=3*B(3) - 3*E(3) + 3*F(3) + B(1) - 3*F(1)
850
851           XCU(IUP)=-3*D(1) + 2*F(1) - 8*A(2) + 5*D(2) - 2*F(2)
852
853           XSQY(IUP)=-3*E(1) - 3*C(2) + 3*E(2)
854
855           XYSQ(IUP)=-3*C(3) + 3*D(3) - 3*D(1)
856
857           YCU(IUP)=-8*B(3) + 5*E(3) - 2*F(3) - 3*E(1) + 2*F(1)
858
859           XFO(IUP)=-3*A(1) + 2*D(1) + 7*A(2) - 2*D(2)
860
861           XCUY(IUP)=-3*C(1) + 2*E(1) + 5*C(2) - 2*E(2)
862
863           XSQYSQ(IUP)=3*A(3) - 9*B(3) + 9*E(3) - 9*F(3) + 9*A(4)
864          1 + 9*B(4) + 9*C(4) - 9*D(4) - 9*E(4) + 9*F(4) - 3*A(1) - 3*B(1)
865          2 + 9*F(1) + 3*B(2) - 9*A(2) + 9*D(2) - 9*F(2)
866
867           XYCU(IUP)=5*C(3) - 2*D(3) - 3*C(1) + 2*D(1)
868
869           YFO(IUP)=7*B(3) - 2*E(3) - 3*B(1) + 2*E(1)
870
871           XFI(IUP)=2*A(1) - 2*A(2)
872
873           XFOY(IUP)=2*C(1) - 2*C(2)
874
875           XCUYSQ(IUP)=9*C(3) - 9*D(3) + 6*B(3) - 6*E(3) + 6*F(3) -
876          1 24*A(4)- 15*C(4) + 15*D(4)- 6*B(4) + 6*E(4)- 6*F(4) + 2*B(1)
877          2 + 9*D(1) - 6*F(1) - 2*B(2) + 24*A(2) - 15*D(2) + 6*F(2)
878
879           XSQYCU(IUP)=-2*A(3) + 24*B(3) - 15*E(3) + 6*F(3) - 24*B(4) -
880          1 15*C(4)+ 15*E(4) - 6*A(4) + 6*D(4) - 6*F(4) + 2*A(1) + 9*E(1)
881          2 - 6*F(1) + 9*C(2) - 9*E(2) + 6*A(2) - 6*D(2) + 6*F(2)
882
883           XYFO(IUP)=-2*C(3) + 2*C(1)
884
885           YFI(IUP)=-2*B(3) + 2*B(1)
886
887           XFOYSQ(IUP)=-9*A(3) - 6*C(3) + 6*D(3) + 21*A(4) + 6*C(4) -
888          1 6*D(4)+ 9*A(1) - 6*D(1) - 21*A(2) + 6*D(2)
889
890           XCUYCU(IUP)=-15*C(3) - 16*B(3) + 10*E(3) + 6*D(3) - 4*F(3) +
891          1 25*C(4)-10*E(4) +16*A(4) -10*D(4) +16*B(4) + 4*F(4) + 9*C(1)
892          2 - 6*D(1) - 6*E(1) + 4*F(1) - 15*C(2) + 6*E(2) - 16*A(2)
893          3 + 10*D(2) - 4*F(2)
894
895           XSQYFO(IUP)=-21*B(3) + 6*E(3) +21*B(4) + 6*C(4)- 6*E(4)+ 9*B(1)
896          1 - 6*E(1) - 9*B(2) - 6*C(2) + 6*E(2)
```

```
      XFIYSQ(IUP)=6*A(3) - 6*A(4) - 6*A(1) + 6*A(2)

      XFOYCU(IUP)=10*C(3) + 6*A(3) - 4*D(3) -10*C(4) -14*A(4) + 4*D(4)
     1 - 6*A(1) - 6*C(1) + 4*D(1) + 6*C(2) + 14*A(2) - 4*D(2)

      XCUYFO(IUP)=14*B(3) + 6*C(3) - 4*E(3) -14*B(4) -10*C(4) + 4*E(4)
     1 - 6*B(1) - 6*C(1) + 4*E(1) + 6*B(2) + 10*C(2) - 4*E(2)

      XSQYFI(IUP)=6*B(3) - 6*B(4) - 6*B(1) + 6*B(2)

      XFIYCU(IUP)=-4*A(3) + 4*A(4) + 4*A(1) - 4*A(2)

      XFOYFO(IUP)=-4*C(3) + 4*C(4) + 4*C(1) - 4*C(2)

      XCUYFI(IUP)=-4*B(3) + 4*B(4) + 4*B(1) - 4*B(2)

C ASSUME 1ST STEPS IN UPSL & DOWNSL DIRN'S(NCOUNT=1)WILL TAKE PLACE IN SAME
C JNJFITTED SQUARE
      IF(NCOUNT.NE.1.OR.IUP.EQ.2)GO TO 30
      CONS(2)=CONS(1)
      XCOEF(2)=XCOEF(1)
      YCOEF(2)=YCOEF(1)
      XSQ(2)=XSQ(1)
      XY(2)=XY(1)
      YSQ(2)=YSQ(1)
      XCU(2)=XCU(1)
      XSQY(2)=XSQY(1)
      XYSQ(2)=XYSQ(1)
      YCU(2)=YCU(1)
      XFO(2)=XFO(1)
      XCUY(2)=XCUY(1)
      XSQYSQ(2)=XSQYSQ(1)
      XYCU(2)=XYCU(1)
      YFO(2)=YFO(1)
      XFI(2)=XFI(1)
      XFOY(2)=XFOY(1)
      XCUYSQ(2)=XCUYSQ(1)
      XSQYCU(2)=XSQYCU(1)
      XYFO(2)=XYFO(1)
      YFI(2)=YFI(1)
      XFOYSQ(2)=XFOYSQ(1)
      XCUYCU(2)=XCUYCU(1)
      XSQYFO(2)=XSQYFO(1)
      XFIYSQ(2)=XFIYSQ(1)
      XFOYCU(2)=XFOYCU(1)
      XCUYFO(2)=XCUYFO(1)
      XSQYFI(2)=XSQYFI(1)
      XFIYCU(2)=XFIYCU(1)
      XFOYFO(2)=XFOYFO(1)
      XCUYFI(2)=XCUYFI(1)

      ENTRY DERIV

C (2)COMPUTE COEFF'S FOR SLOPE VECTOR
C (EACH X BECOMES X+P;EACH Y Y+Q,TO MAKE FOR ORIGIN ALWAYS AT RX(IUP),RY(IUP))
   30 P=RX(IUP)
      Q=RY(IUP)
      DEE=XCOEF(IUP)+ XSQ(IUP)*2*P+ XY(IUP)*Q + XCU(IUP)*3*P*P
     1 +XSQY(IUP)*2*P*Q + XYSQ(IUP)*Q*Q
     2 + XFO(IUP)*4*P*P*P + XCUY(IUP)*3*P*P*Q + XSQYSQ(IUP)*2*P*Q*Q
     3 + XYCU(IUP)*Q*Q*Q + XFI(IUP)*5*P*P*P*P + XFOY(IUP)*4*P*P*P*Q
     4 + XCUYSQ(IUP)*3*P*P*Q*Q
     4 +XSQYCU(IUP)*2*P*Q*Q*Q + XYFO(IUP)*Q*Q*Q*Q
```

```
     5 + XFOYSQ(IUP)*4*P*P*P*P*Q*Q + XCUYCU(IUP)*3*P*P*Q*Q*Q
     6 + XSQYFO(IUP)*2*P*Q*Q*Q*Q + XFIYSQ(IUP)*5*P*P*P*P*P*Q*Q
     7 + XFOYCU(IUP)*4*P*P*P*P*Q*Q*Q + XCUYFO(IUP)*3*P*P*Q*Q*Q*Q
     8 + XSQYFI(IUP)*2*P*Q*Q*Q*Q*Q + XFIYCU(IUP)*5*P*P*P*P*P*Q*Q*Q
     9 + XFOYFO(IUP)*4*P*P*P*P*Q*Q*Q*Q + XCUYFI(IUP)*3*P*P*Q*Q*Q*Q*Q

      EEE=YCOEF(IUP)+ XY(IUP)*P + YSQ(IUP)*2*Q + XSQY(IUP)*P*P
     1 + XYSQ(IUP)*2*P*Q
     2 + YCU(IUP)*3*Q*Q + XCUY(IUP)*P*P*P + XSQYSQ(IUP)*2*P*P*Q
     3 + XYCU(IUP)*3*P*Q*Q + YFO(IUP)*4*Q*Q*Q + XFOY(IUP)*P*P*P*P
     4 + XCUYSQ(IUP)*2*P*P*P*Q +XSQYCU(IUP)*3*P*P*Q*Q
     5 + XYFO(IUP)*4*P*Q*Q*Q
     6 + YFI(IUP)*5*Q*Q*Q*Q + XFOYSQ(IUP)*2*P*P*P*P*Q
     7 + XCUYCU(IUP)*3*P*P*P*Q*Q + XSQYFO(IUP)*4*P*P*Q*Q*Q
     8 + XFIYSQ(IUP)*2*P*P*P*P*P*Q + XFOYCU(IUP)*3*P*P*P*P*Q*Q
     9 + XCUYFO(IUP)*4*P*P*P*Q*Q*Q + XSQYFI(IUP)*5*P*P*Q*Q*Q*Q
     8 + XFIYCU(IUP)*3*P*P*P*P*P*Q*Q + XFOYFO(IUP)*4*P*P*P*P*Q*Q*Q
     7 + XCUYFI(IUP)*5*P*P*P*Q*Q*Q*Q


C (3)SUBSTITUTE IN TO FIND HEIGHT AT X(NCOUNT,IUP),Y(NCOUNT,IUP)
      ALT(NCOUNT,IUP)=CONS(IUP) + XCOEF(IUP)*P + YCOEF(IUP)*Q
     1 +XSQ(IUP)*P*P + XY(IUP)*P*Q
     2 + YSQ(IUP)*Q*Q + XCU(IUP)*P*P*P + XSQY(IUP)*P*P*Q
     3 + XYSQ(IUP)*P*Q*Q + YCU(IUP)*Q*Q*Q + XFO(IUP)*P*P*P*P
     4 + XCUY(IUP)*P*P*P*Q + XSQYSQ(IUP)*P*P*Q*Q
     5 + XYCU(IUP)*P*Q*Q*Q + YFO(IUP)*Q*Q*Q*Q
     6 + XFI(IUP)*P*P*P*P*P + XFOY(IUP)*P*P*P*P*Q
     7 + XCUYSQ(IUP)*P*P*P*Q*Q + XSQYCU(IUP)*P*P*Q*Q*Q
     8 + XYFO(IUP)*P*Q*Q*Q*Q + YFI(IUP)*Q*Q*Q*Q*Q
     9 + XFOYSQ(IUP)*P*P*P*P*Q*Q + XCUYCU(IUP)*P*P*P*Q*Q*Q
     8 + XSQYFO(IUP)*P*P*Q*Q*Q*Q + XFIYSQ(IUP)*P*P*P*P*P*Q*Q
     7 + XFOYCU(IUP)*P*P*P*P*Q*Q*Q + XCUYFO(IUP)*P*P*P*Q*Q*Q*Q
     6+XSQYFI(IUP)*P*P*Q*Q*Q*Q*Q + XFIYCU(IUP)*P*P*P*P*P*Q*Q*Q
     5 + XFOYFO(IUP)*P*P*P*P*Q*Q*Q*Q
     4 + XCUYFI(IUP)*P*P*P*Q*Q*Q*Q*Q

      IF(NCOUNT.EQ.1)GO TO 10
C INCLINATION OF LINE JOINING THIS PROFILE STATION AND THE 1 BEFORE IT
      DIFFA=ALT(NCOUNT,IUP)-ALT(NCOUNT-1,IUP)
      IF(IUP.EQ.1.AND.DIFFA.LT.0.0)GO TO 20
      IF(IUP.EQ.2.AND.DIFFA.GT.0.0)GO TO 20
      ANGDEG(NCOUNT-1,IUP)=(DATAN2(DIFFA,STEP))*57.29578
   10 RETURN

C TERMINATION FOR ANGULAR REVERSE NOT PICKED UP BY DERIVATIVE(ADDED 2.2.83)
   20 NFLG(IUP)=6
      NUPDOW(IUP)=NCOUNT-1
      RETURN

      END
```

Appendix 1b Explanation of input required by SLOPROFIL.2

```
DETAILS TO BE INPUT ON UNIT 5 FOR RUN OF 'SLOPROFIL.2'
------------------------------------------------------
1)TITLE OF RUN (MAX.20 CHARACTERS)

2)NUMBER OF COLUMNS IN MATRIX (FORMAT I3)

3)NUMBER OF ROWS IN MATRIX (FORMAT I3)

4)NUMBER OF DATA VALUES PER ROW IN MATRIX FILE (FORMAT I2)

5)GRID MESH SIZE IN METRES (FORMAT F6.2)

6)MATRIX ALTITUDE UNITS:INPUT 1 IF IN METRES,0 IF FEET

7)MAX.NO.OF STEPS TO BE TAKEN BY PROFILE IN EACH DIRECTION FROM STARTING-POINT
       ('NHOPS':UPPER LIMIT 9999);
  MAX.LOCAL ORIENTATION CHANGE ALLOWED('ORCJ');
  MAX.ORIENTATION CHANGE ALLOWED OVER WHOLE PROFILE('GLOBAL');
  STEPLENGTH IN MATRIX CO-ORD UNITS('STEPLN')
                                          .......FORMAT(I4,2F6.2,F5.3)

8)IF LIST OF CO-ORD'S,HEIGHTS,GRADIENTS,ORIENT'S FOLLOWED FOR EACH PROFILE
  REQUIRED(1 Y,0 N)

9)IF THERE'S ADDITIONAL INFO TO PLOT(EG DIG CONT'S),ENTER 1;IF NOT,0

10)WHICH STARTER-POINT OPTION IS REQUIRED:-
  ENTER 1 IF PROFILE STARTING-POINTS TO BE RANDOM VERTICES,OR
        2 IF THEY ARE TO BE SYSTEMATIC VERTICES(GRID PATTERN),OR
        3 IF THEY ARE IN ANOTHER FILE AS CO-ORDINATES

11)IF ANS TO (10) WAS 1:-
  ENTER NUMBER OF RANDOM VERTICES REQUIRED (FORMAT I4)

IF ANS TO (10) WAS 2:-
  ENTER SPACING OF SYSTEMATIC VERTICES - EG ( 1) IF EVERY VERTEX,( 2) IF
                                 EVERY OTHER,ETC (FORMAT I2),AND
  ENTER CO-ORD'S OF TOP LH VERTEX REQUIRED (FORMAT 2I3)

IF ANS TO (10) WAS 3:-
  ENTER NUMBER OF DIGITIZED CO-ORDINATES (FORMAT I4)
  ENTER 1 IF USING STREAM & DIVIDE STARTING-POINTS;FOLLOWED ON NEXT LINE BY
      HOW FAR AWAY FROM STREAM OR DIVIDE YOU WANT PROFILES TO START(IN MULTI-
      PLES OF STEPLENGTH)AND A 1 IF SINGLE PROFILES DESIRED,2 FOR PAIRED
      PROFILES(FORMAT F5.2,I1).
  ENTER 0 IF STARTING-POINTS NOT STREAM & DIVIDE
```

Appendix 1c

Sample of input for SLOPROFIL.2

This specifies that the matrix lies within a rectangular area of 160 x 162 grid points (stored in a file with 20 points per row), at 50m mesh and coded in feet (rows 2 to 6 inclusive of listing). Terminating conditions for the profiles to be traced are as follows: NHOPS = 9999, ORCJ = 10°, GLOBAL = 35° and steplengths = 0.1 times the matrix mesh size (=5m) (row 7). No detailed listing is required, and no additional digitized information for plotting is to be input (rows 8 and 9). The profiles are to be generated from a grid pattern of points of origin, taking every 10th vertex and starting with the vertex(1,1)(rows 10 to 12).

```
1     GARA,GRID SAMPLE
2     160
3     162
4     20
5      50.0
6     0
7     9999 10.0  35.0 0.1
8     0
9     0
10    2
11    10
12      1  1
```

Appendix 2a

Listing of field profile data for Gara catchment

Ground surface length (gsl) = 5m

For each profile listing includes:-

1. profile name
2. number of gsl's measured
3. gradients of gsl's in degrees, listed in the order encountered in a descent from profile crest. (reverse slope angles marked negative)
4. bearings of gsls (from their upslope ends) in degrees clockwise from north, listed in the same order as in (3)
5. number of times profile line had to be offset (e.g. because of obstacle)
6. if answer to (5) was >0, the no. of the profile station the offset was made at (NB station 1 is crest of profile), the distance offset in metres, the bearing of offset (from its upslope end), and the inclination of the offset line in degrees (negative if reverse slope); FORTRAN format (I3, F6.2, 2F5.1)
7. number of places at which plan curvature readings were taken.
8. if answer to (7) was >0, the no. of the profile station the planc readings were taken at, and the readings obtained over 20m, and over 10m (if any), either side of profile line; FORTRAN format (I3, 2F5.1).
9. details about the point of origin of the profile : the no. of the profile station it fell at, its coordinates (in the coordinate system of the Gara matrix), and its altitude in metres; FORTRAN format (I3, 2F8.4, F7.2).

```
  1
 63
  1.5  2.0  2.0  2.5  3.0  3.0  3.0  3.5  4.0  4.0  4.0  4.0  4.0  4.5  5.5  4.0
  7.0  5.0  7.0  5.5  5.0  4.5  4.5  4.5  4.0  4.5  4.5  5.0  6.5  7.0  7.0  7.5
  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0  9.0  9.0
  9.0  8.5  8.0  9.0  8.5  9.0 11.0 12.0 14.0 17.0 18.0 18.0 17.0 17.0 17.0
141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0
141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0
141.0141.0141.0141.0141.0141.0141.0141.0141.0141.0151.0151.0151.0151.0151.0151.0
151.0151.0151.0151.0151.0151.0151.0151.0151.0151.0151.0151.0151.0151.0151.0
  0
  1
 39196.0
 43116.0   139.0    109.73

  4
 21
  5.5  5.5  6.5  7.0  9.0 11.0 12.0 15.0 15.0 16.0 20.5 21.0 21.5 21.0 22.0 21.0
 20.0 18.0 15.5 12.0  9.0
127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5127.5
127.5127.5127.5127.5127.5
  0
  1
 19170.5170.5
 15116.0   116.0     83.52

  5
 28
  7.0  9.0  9.0 10.5 13.0 14.0 16.0 17.5 18.5 21.0 21.0 21.0 18.0 28.5 21.5 25.0
 26.0 24.0 23.5 22.0 20.5 22.0 23.0 22.5 23.5 24.0 23.0 21.5
274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0276.0276.0276.0
276.0276.0276.0276.0276.0276.0276.0276.0276.0276.0276.0
  0
  1
  8160.0165.0
  9139.0   116.0     67.06

  6
 88
 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 13.0 15.0 13.5 14.0 13.0 12.0
 11.0 10.0  9.0  9.0  8.0  8.0  8.0  8.0  9.0  8.0 10.0 10.0  0.0 13.0 10.0  6.0
  7.0  9.0 10.0 12.0 15.0 17.0 14.0 10.0 13.0 13.0 14.0 11.0  8.0 11.0 12.5 12.0
 13.0 16.5 16.0 15.5 16.5 15.0 15.0 13.5 11.0 11.0 11.0 11.0 10.5 10.5 10.0 11.5
  9.5 12.0  7.5  7.5 10.5 11.0  7.0  6.5  9.0  7.0  8.5  6.0  5.5  5.5  7.0  7.0
  6.0  8.0  7.0  6.0  4.5  4.5  2.0  2.0
 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0
 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 49.0 79.0 79.0 79.0 79.0
 79.0 79.0 79.0 79.0 79.0 79.0 79.0 79.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 35.0 35.0 35.0 35.0 35.0 35.0
 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 22.0 22.0 22.0 22.0
 22.0 22.0 22.0 22.0 22.0 22.0 22.0 22.0
  0
  2
 31123.5142.0
 55 96.0104.0
  1 70.0    93.0    168.25
```

```
  7
 34
  0.0  0.5  1.0  1.0  1.5  2.0  2.0  4.0  4.0  5.0  5.0  5.0  6.0  6.5  7.0  6.5
  7.0  7.0  8.5 10.0 11.5 12.0 12.0 11.0 11.0 10.5  9.0  8.0  6.5  6.5  6.0  6.0
  6.0  6.0
192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0
192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0192.0
192.0192.0
  0
  1
 26181.0180.0
 18 93.0    93.0    121.31

  8
 54
  4.0  4.0  4.0  4.5  5.0  5.5  6.0  5.5  6.0  6.0  6.0  6.0  6.0  6.0  6.5  6.5
  6.0  6.5  6.5  7.0  7.0  7.5  8.0  8.5  8.5  8.5  8.5  9.0  9.0  9.5 10.0 10.5
  9.0 10.0  9.5 10.0  8.5 11.0 12.0 13.0 14.0 16.0 15.5 13.5 15.0 30.0 12.5 19.0
 22.0 19.0 18.5 13.5  9.0  1.0
200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0
200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0
200.0200.0200.0200.0200.0200.0200.0172.0172.0172.0172.0172.0172.0172.0172.0172.0
172.0172.0172.0172.0172.0172.0
  0
  1
 45198.0189.0
 47116.0    93.0     58.52

  9
 64
  0.0  1.0  1.0  2.0  1.5  2.0  2.0  2.0  3.0  2.5  4.0  6.0  5.5  6.0  6.0  7.0
  8.0 10.0 10.0 12.0 13.0 14.0 14.0 14.5 13.0 13.0 11.0 11.0 12.0  6.0  5.5  6.0
  7.0  7.0  9.0 10.5  9.5  9.0  9.0  8.0  8.0  7.5  7.5  8.0  7.5  7.5  7.0  6.0
  7.0  7.0  6.5  6.5  7.0  7.0  8.0  9.0  9.0  8.5  9.0  8.5  8.5  8.0  7.0  5.5
178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0
178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0178.0196.0196.0196.0196.0
196.0196.0199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5
199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5199.5
  0
  1
 53186.0179.0
 53139.0    93.0    135.33

  10
 64
  1.5  1.5  1.5  1.0  2.0  2.0  1.0  2.0  1.0  2.0  2.0  2.5  3.0  3.0  4.0  3.0
  3.0  3.0  3.0  3.0  3.5  3.5  3.0  4.0  4.0  4.0  3.0  4.0  4.0  4.0  4.5  4.0
  3.5  3.5  4.0  3.0  4.5  5.0  5.0  5.5  5.0  5.0  6.0  7.0  9.0 11.0 13.0 14.0
 14.0 16.0 14.5  8.5 25.0 15.0 18.0 17.0 17.5 17.0 16.0 10.0  2.0  3.0  4.0  2.0
100.0100.0100.0100.0100.0100.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0
102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0102.0
102.0102.0102.0102.0102.0102.0102.0102.0114.0114.0114.0114.0114.0114.0114.0114.0
114.0114.0114.0114.0116.0116.0116.0116.0116.0116.0116.0116.0116.0116.0116.0116.0
  0
  1
 47246.5214.0
 54 47.0    70.0     98.76
```

```
 11
27
 1.0  1.0  2.0  2.5  4.0  3.5  5.5  5.5  6.0  7.0  7.0  7.0  8.0  8.0  8.0  7.5
 8.0  8.0  8.5  9.0  9.0  8.0 13.0 15.0 15.0 16.0 12.5
274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0
274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0274.0
 0
 1
19179.5173.0
 1 70.0    70.0    107.29

 12
73
 1.0  1.0  1.0  2.0  2.5  3.5  3.0  2.0  1.0  3.0  3.0  3.0  3.0  3.5  3.0  3.0
 2.5  3.0  3.0  3.5  3.0  3.0  3.0  3.0  3.5  3.0  3.5  4.0  4.5  4.0  4.0  5.0
 6.0  6.0  7.5  8.0  9.0 11.0 14.5 18.0 15.0 12.0  9.5 20.0 18.0 19.0 22.0 22.0
22.5 22.5 23.0 21.5 22.0 21.0 20.0 19.5 20.0 18.5 16.5 17.0 17.0 19.0 18.5 15.0
16.0 12.5 11.0  7.0  6.0  6.0 -0.5 -2.0  1.0
202.0202.0202.0202.0202.0202.0202.0209.0209.0209.0209.0209.0209.0209.0209.0209.0
209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0
209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0209.0207.0207.0207.0207.0207.0
207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0207.0
207.0207.0207.0207.0207.0207.0207.0207.0207.0
 0
 0
68 93.0    70.0     58.52

 13
47
 1.0  1.0  1.0  2.0  2.5  2.5  3.0  4.0  3.5  4.0  4.5  5.5  5.5  4.5  5.5 15.0
 6.5 11.0 13.0 13.0 14.0 14.0 13.0 19.0 18.0 19.0 19.5 19.0 15.0 18.0 17.0 17.0
14.5 16.0 11.5 14.5 19.0 12.5 14.5 14.0 16.0 17.0 15.5 15.0 18.0 15.0  6.5
320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0
320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0
320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0320.0
 0
 0
33116.0    70.0     95.10

 15 & I
52
 5.5  8.0  8.5  8.5  8.0  8.0  7.0  7.0  7.0  6.5  7.0  6.5  6.5  5.5  4.5  4.0
 4.0  4.0  3.0  4.0  1.0  0.0  2.0  4.0  2.0  0.0  2.0  4.0  4.0  2.5  2.5  2.0
 1.5  2.0  2.5  3.0  2.0  3.0  3.0  4.0  4.0  5.0  5.0  7.0  5.5  6.0  3.5  3.0
 3.0  3.0  2.0  6.0
147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0147.0
147.0147.0147.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0
140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0140.0
140.0140.0140.0140.0
 0
 1
41168.0168.0
27 46.5    48.5    134.11

 16
42
 2.0  2.0  2.5  2.0  3.0  3.0  3.0  4.5  4.0  4.0  7.0  7.5  9.0 12.0 16.0 16.0
17.0 15.0 14.5 12.5 12.0 10.5 12.0 12.0 12.5 14.0 13.0 13.5 14.0 12.5 14.0  7.0
 9.0  8.0  7.0  8.0  7.0  8.0 10.0 13.0 13.0 13.0
42.0 42.0 42.0 42.0 42.0 42.0 42.0 42.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0
36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 36.0 34.0 34.0
34.0 34.0 34.0 34.0 34.0 34.0 34.0 34.0 34.0 34.0
 0
 1
25181.5179.5
24 70.0    47.0    107.90
```

```
  18
 67
  4.0  3.0  3.5  3.0  3.0  4.0  3.5  3.5  3.0  5.0  4.0  3.0  3.0  3.5  4.0  4.0
  4.0  5.0  5.0  6.0  6.0  6.0  6.5  7.0  7.0  7.0  7.0  7.5  7.5  8.0  7.5  8.0
  8.5  8.5  8.0  9.0  9.0 10.0 10.0  8.5  7.0 15.0  7.0 10.5 11.5 12.0 13.0 12.5
 12.5 12.0 12.5 12.0 12.0 12.0 12.5 12.0 13.0 13.0 14.0 15.0 16.0 15.0 14.0 13.0
 12.5 10.0 12.0
200.0200.0200.0200.0200.0200.0200.0200.0200.0200.0196.0196.0196.0196.0196.0200.0
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200.0200.0200.0200.0200.0200.0200.0200.0200.0195.0195.0195.0195.0195.0195.0195.0
195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0195.0
195.0195.0195.0
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  1
 62178.5181.0
 62116.0    47.0    119.48

  19
175
  3.5  1.0  1.5  2.0  1.5  1.0  0.5 -0.5  1.0  1.5  1.0  0.5  0.0  0.0  0.5  1.0
  1.0  1.0  1.0  1.5  1.5  1.5  0.5  1.5  1.0  1.0  1.5  1.5  2.0  1.5  1.5  0.0
  2.0 -0.5  2.0  2.5  2.0  2.0  2.5  2.5  1.5  2.0  2.0  2.5  2.5  2.0  1.5  2.0
  3.0  2.5  3.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.5  2.5  3.0  5.0
  0.0  3.0  2.5  2.5  3.5  3.5  3.0  2.0  2.5  3.0  3.0  3.0  2.0  2.5  2.5  3.0
  2.0  2.0  2.0  3.0  3.0  3.0  2.5  4.0  4.0  4.0  3.0  3.5  3.5  3.5  3.5  3.5
  3.5  3.5  3.5  5.0  1.0  2.0  4.0  4.5  2.0  1.5  4.5  4.0  4.0  5.0  4.0  5.0
  5.0  5.0  5.5  5.5  6.0  6.5  6.5  6.5  7.0  7.0  7.0  6.0  6.0  6.0  6.0  6.0
  6.0  6.0  6.0  6.0  6.0  5.0  5.0  4.5  5.0  5.0  5.0  6.0  5.5  6.0  5.0  5.5
  5.5  3.0  4.0  3.0  4.5  4.0  5.0  6.0  5.0  6.0  5.0  5.5  5.0  4.0  5.0  6.0
  5.0  5.5  6.0  6.0  6.0  5.5  6.5  6.5  6.0  5.0  5.0  5.0  5.0  5.0  6.0
131.0131.0131.0131.0131.0131.0131.0131.0 74.0 74.0 74.0 74.0 74.0 74.0 74.0 74.0
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  2
 33 20.0 332.0  1.5
 35 60.0 332.0  1.0
  1
 54142.0
176 47.0    24.0    160.32

  20
 40
  2.5  3.0  3.0  3.0  4.0  4.0  4.0  4.0  3.5  4.0  3.5  4.5  4.5  5.0  4.5  5.0
  5.5  5.0  5.5  5.5  6.0  6.0  7.0  7.0  6.5  7.0  7.0  7.0  7.0  7.0  7.0  7.0
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305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0305.0
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305.0305.0305.0305.0305.0305.0305.0305.0
  0
  1
 23170.5172.0
 23 70.0    24.0    166.42
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  A
 27
  5.0  4.5  5.0  5.0  5.0  7.0  7.0  7.5  9.0  8.5  8.0  8.0  8.0  9.5  9.0 10.0
  8.5  7.5 25.0 25.0 25.0 25.0 25.0 25.0 24.0 19.0 15.0
173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0
173.0173.0173.0173.0173.0173.0173.0173.0173.0173.0
  0
  1
 13183.0182.5
 15120.5894146.2043  89.23

  D
 23
  4.0  4.0  4.5  4.5  6.5  8.5 11.5 10.5 13.0 15.0 16.5 17.5 19.0 19.0 19.0 18.0
 18.5 17.5 18.5 16.0 16.5 16.0 13.0
225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0225.0
225.0225.0225.0225.0225.0225.0
  0
  1
  4185.0185.0
 16100.5501101.4106 102.82

  F
 14
  2.5  3.5  6.0  7.0  9.0 13.0 15.0 16.5 17.0 19.0 19.0 17.0 14.0 14.0
121.0121.0121.0121.0121.0121.0121.0121.0121.0121.0121.0121.0121.0
  0
  1
  9176.0177.5
  5 61.8861 86.9902 146.32

  G
 32
  4.5  6.0  7.0  7.0  7.0  8.0  9.0 10.5 11.5 12.0 12.5 12.5 11.5 10.0  8.0  6.0
  5.0  5.0  6.0  7.0  7.0  8.0  7.0  7.0  6.0  6.5  8.0  7.5  7.0  4.5  3.5  3.0
350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0
350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0350.0
  0
  0
 33 46.8762 79.4460 137.25

  H
 44
  1.0  1.5  1.0  2.0  2.0  2.0  3.0  3.0  3.5  4.0  4.0  5.0  5.5  5.5  5.5  5.5
  5.5  6.0  6.0  6.5  7.0  7.0  8.0  8.0  8.5  9.0 10.0 10.0 10.5 11.5 11.0 11.0
 10.0  9.5  9.0  9.0 12.5  8.5  4.0  2.0  4.0  3.0  3.5  2.0
267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0
267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0267.0
267.0267.0267.0267.0267.0267.0261.0261.0261.0261.0261.0261.0
  0
  1
 33178.5176.5
 14 38.1140 49.0727 139.94
```

```
  J
154
  2.5  3.0  3.0  4.0  3.5  3.5  4.0  4.0  5.0  4.0  3.0  4.0  4.5  5.0  4.5  5.0
  5.0  4.0  5.0  5.0  5.0  5.0  6.0  6.0  7.0  8.5  5.0  5.0  6.0  6.0  5.5  6.0
  6.0  7.0  7.5  8.0  7.0  7.0  7.5  9.5  9.0 11.0  8.5  6.0  6.0  4.5  4.0  7.0
  7.5  7.0  7.0  6.5  6.0  5.0  5.5  5.0  5.0  5.0  6.0  5.0  5.5  5.0  4.0  4.0
  4.0  5.0  5.0  5.0  4.5  4.5  5.5  3.0  2.5  2.5  3.0  3.5  5.0  3.5  4.5  4.0
  4.0  4.5  4.5  5.0  4.5  4.0  3.5  3.5  3.5  4.0  4.0  3.5  4.0  4.0  4.0  4.0
 10.0  2.0  3.0  3.5  4.0  4.0  4.0  4.5  4.0  4.5  5.0  4.5  5.0  4.5  5.0  4.5
  5.0  4.5  4.5  4.5  4.0  4.0  4.0  5.0  4.5  4.0  3.5  4.0  4.5  4.0  5.5  5.0
  6.0  7.0  8.0  9.0  8.5  8.0 10.0 11.0 14.0 14.0 16.0 14.5 14.0 13.5 12.5 14.5
  9.5  8.0 11.0 14.0 18.0  8.5 13.5 11.5  3.5  1.0
113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0
113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0113.0133.0133.0
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143.0143.0143.0143.0143.0143.0143.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0
 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0 96.0
 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0 87.0
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 87.0 87.0 87.0 87.0 87.0 87.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0
 81.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0 81.0
  0
  1
143186.0187.0
121 59.1356 38.8958 125.15

  L
106
  0.0  0.0  0.0  0.0  1.5  1.0  1.0  1.0  1.0  1.5  2.0  2.0  2.0  2.0  2.5  2.0
  2.0  2.5  2.0  2.5  3.0  3.0  4.0  3.5  4.0  4.0  4.0  4.0  3.0  3.5  3.0  4.5
  3.0  1.0  2.0  2.5  3.5  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.5  5.0  5.5
  5.0  5.5  5.5  5.0  6.0  5.0  5.0  5.0  4.0  4.0  3.5  4.0  4.0  4.0  3.5  4.0
  4.0  4.0  4.5  4.0  4.0  5.0  5.5  6.0  6.5  0.0  2.0  2.0  3.5  4.0  4.0  4.0
  4.5  4.0  4.5  5.0  4.5  4.0  3.5  3.5  4.0  4.5  4.0  4.0  6.0  6.0  6.0  6.0
  8.0  3.5  3.0  4.0  5.0  5.0  5.5  4.5  5.0  4.0
136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0
136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0
136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0
136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0136.0
136.0136.0126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5
126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5
126.5126.5126.5126.5126.5126.5126.5126.5126.5126.5
  0
  1
 25195.0182.0
107 71.3556 11.4695 161.31

  M
 61
  5.0  6.0  6.0  5.5  7.0  9.5  8.5  6.5  8.0  8.5 12.0 13.0 12.0 11.5 10.0 10.0
  9.0  8.0  8.0  7.5  7.5  8.0  7.5  7.0  8.5  6.0  4.0  4.0  5.0  5.5  6.0  6.5
  6.5  7.0  7.5  8.0  8.5  8.0  8.0  8.0  8.0  7.5  7.0  7.0  6.5  6.0  6.0  6.5
  7.0  8.0  9.0 11.0 13.0 15.5 16.0 19.0 17.5 15.0  5.0  2.5  4.0
273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0
273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0
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273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0273.0
  0
  1
 51178.5174.5
  7 82.7112 41.1355 127.34
```

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  N
 51
  4.0  4.0  5.0  5.0  5.0  5.0  5.0  5.0  4.5  5.0  5.0  5.0  5.0  5.0  5.0  5.0
  5.0  5.0  6.0  6.5  8.0  6.5  5.0  7.0  7.0 11.0 12.0 12.5 11.5 12.0 11.0 11.0
 10.5 11.0 11.0 11.0 11.0  9.5  9.5  8.5 11.0 11.0 11.5 12.0 14.0 15.0 16.0 17.0
 15.0 20.5 19.0
278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0278.0
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293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0293.0
293.0293.0293.0
  0
  1
 18190.0161.0
 18 90.4912 63.2966 102.82

  O
 37
  1.0  0.0  1.0  0.5  1.0  1.0  1.5  2.0  1.0  1.0  2.0  3.0  2.0  3.0  4.0  3.5
  4.0  4.0  3.5  4.0  5.0  4.5  5.0  4.0  5.0  6.0  6.0  6.0  6.0  6.5  6.5  7.5
  7.0  8.5  9.0  9.0  5.0
266.0266.0266.0266.0266.0266.0266.0266.0268.0268.0268.0268.0268.0268.0268.0268.0
268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0268.0
268.0268.0268.0268.0268.0
  0
  0
 24110.4126 26.4793 162.20

  P
 25
  0.0  0.0  1.0  3.0  3.0  5.0  6.0  4.0 10.0  8.5  7.0  9.0 10.0 13.0 15.0 19.0
 21.5 23.0 23.0 22.5 22.5 21.0 21.0 22.5 19.5
309.0309.0309.0309.0309.0309.0309.0309.0311.0311.0311.0311.0311.0311.0311.0311.0
311.0311.0311.0311.0311.0311.0311.0311.0311.0
  0
  1
 20179.5178.0
 19 96.6994 75.9096  65.71

  Q
 35
  4.0  8.0  8.5  9.0 10.0 11.0 12.0 12.5 14.0 14.0 17.5 21.0 21.0 22.0 23.5 24.0
 21.0 22.0 19.0 19.5 18.5 18.0 18.0 18.0 18.5 17.0 16.0 13.0 16.0 17.0 18.5 16.0
 12.0  8.5  1.5
301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0
301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0301.0
301.0301.0301.0
  0
  1
 23169.5175.5
 18104.0865 78.9744  73.70
```

```
  R
 81
  0.0  0.0  0.5  2.5  1.0  1.0  2.0  2.0  2.0  2.0  2.0  3.0  3.5  3.0  4.0  3.5
  4.0  4.0  4.5  4.5  4.5  4.0  3.5  3.5  5.0  5.0  4.5  4.0  4.0  5.0  5.0  4.0
  4.0  4.0  3.0  3.5  4.0  3.5  4.0  4.0  4.0  4.0  4.0  4.5  6.0  6.0  5.0  5.0
  5.0  5.0  5.0  5.0  6.0  5.0  7.0  8.5 10.0 11.5 12.0 11.0 15.0 16.0 17.0 16.0
 14.0 16.0 14.0 14.5 15.0 15.0 14.0 14.0 13.5 14.0 14.0 14.0 14.0 14.0 14.0 13.5
 10.0
261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5
261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5261.5
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302.0302.0309.0309.0309.0309.0309.0309.0309.0309.0309.0309.0309.0309.0309.0
309.0
  0
  1
 67172.0173.0
 63112.7309 88.3261  67.94

   1
 53
  8.0 10.5 11.0 12.0 14.5 17.5 19.0 19.0 14.0 19.0 18.0 18.0 19.0 20.0 20.0 20.5
 22.0 22.0 21.0 21.0 21.0 20.0 21.0 21.5 23.0 22.0 23.0 19.0 22.0 21.0 21.0 21.0
 21.0 21.5 21.0 22.0 22.0 22.0 22.0 22.0 24.0 23.0 21.5 19.0 18.5 22.0 23.5 22.0
 21.0 22.0 16.0  8.5  4.5
331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0
331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0
331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0331.0325.0325.0325.0
325.0325.0325.0325.0325.0
  0
  0
  9142.5540126.6365  89.78
```

Appendix 2b

Listing of field profile data for Netherhearth catchment

Ground surface length (gsl) = 1.52 m

For each profile listing includes:-

1. profile name
2. number of gsl's measured
3. gradients of gsl's in degrees, listed in the order encountered in a descent from profile crest (Reverse slope angles marked negative)

```
  1
31
   0    0    0  0.5  6.0 -0.5  4.5  3.0  2.5  2.0  2.0  4.0  2.5  3.0  7.0  7.0
 8.0 17.5  7.5  6.0  6.5 14.5  5.0  4.5 17.5 14.0 15.5  7.5  3.5 20.0 25.5

  2
18
 2.0  0.5    0  1.0  1.5  5.0  2.5  8.5 14.0  5.0  6.5 14.5 14.0 20.0 37.0    0
28.5 10.0

  3
29
 3.0  1.5  4.0  1.0    0  3.0  1.5  2.0  3.5  3.0  6.5  3.5 -0.5  7.5  8.0 14.0
18.0 10.5  9.0  9.0 13.5  9.0  6.0  2.0 11.5 28.0  0.5  1.0  0.5

  4
19
 3.0  4.0  2.0  3.0  5.0 -0.5  6.0  7.0  5.5  7.0  6.5  9.0 13.0 31.0  8.5 15.0
18.0 19.0 27.0

  5
10
 0.0  7.0  6.5 15.0 45.0 27.0 15.5 31.0 18.0 15.0

  6
29
 5.0  4.5  3.5  6.5  4.5  3.0  7.0  4.5  8.5  7.0  5.5  9.0 10.0 21.5 24.0 13.5
15.0 18.0 19.5 26.0  1.5    0  6.5  0.5 -1.5 -0.5 -1.0    0  9.0

  7
38
 5.0  4.5  3.0  0.5  6.0  3.5    0  2.0  2.0  5.0  5.0  7.0    0  3.0  3.0  2.5
 4.0  4.5  4.0  5.5  3.5 -1.0  7.0 10.5  0.5  9.0 12.0 10.0 20.0 13.0 12.0  6.5
 5.0 14.5  9.0  9.5  4.5    0

  8
30
 7.5  4.5  4.0  5.5  5.0  7.5  5.5  5.0  7.5  2.0 10.0  5.0  8.0  6.5  9.5  7.0
 5.0  8.0  7.5  4.0 10.5  4.0 13.5  8.5 12.5 36.0 10.0 17.0 20.0 10.0

  9
66
 7.0  6.5  4.5  4.5  4.5  7.0  2.0  7.0  5.0  8.0  4.0  9.5  6.5  8.0  7.5  1.0
 6.5  7.0  6.5  9.5  9.0  4.0  7.5  8.5  8.0 16.0 15.0 13.5  9.0  8.0    0  7.0
 5.0  5.0  3.5  4.5  9.5  7.0  5.0  4.5  8.0  1.5  3.0  7.0  6.0  5.0  9.0  4.0
 9.0 12.0 36.0  1.0 -3.0-13.0  5.5  6.5  9.0 28.0 29.0  9.5 11.5  7.5  6.0  9.0
11.0 28.5

 10
26
   0  4.5  5.0  5.0  6.0  5.5  2.0  8.0  4.0  8.0  8.0  8.0  7.5  6.5  5.5  8.5
 9.5 18.5 14.5 13.0 13.5 20.5 25.0 18.5  1.0    0

 11
63
 4.0    0  4.0  2.5  4.5  3.5  4.0  4.5  5.5  2.0  5.5  4.0  6.0  4.5  6.0    0
 7.0  0.5 11.0  3.5  6.5  5.0  6.5  3.5  2.0  5.0  9.0  7.0  4.5  4.0  4.5  3.0
 5.0  4.5  6.0 12.0  8.5  1.0  7.0  8.5 11.0 13.5 10.5  3.5  9.0  7.5  6.0  8.0
14.5 14.5 16.0  3.0    0  5.0  7.0  6.0 25.5 25.0  2.0 13.0 22.0 13.5 20.0
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12
39
6.5 3.0 1.0 0 2.0 0 5.0 4.5 8.0 7.5 2.5 9.0 -0.5 5.5 0 5.0
4.0 5.0 6.0 8.0 8.0 11.0 8.5 5.5 0.5 18.0 24.5 16.5 19.5 12.5 1.0 7.5
-4.0 0 -1.0 1.5 -1.0 0.5 4.5

13
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14
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7.0 4.0 -1.0 6.0 7.0 11.0 14.5 12.0 3.0 6.0

15
375
0.5 0.5 1.0 4.0 0 0.5 0 0.5 0.5 2.0 4.0 3.5 2.0 2.5 4.5 1.0
1.5 0 0.5 5.0 0 0 3.0 3.5 0 6.0 3.0 5.5 6.5 5.0 6.0 5.0
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3.0 4.0 4.0 0.5 4.0 4.5 6.0 19.0 27.0 14.0 -2.0 0 6.0 5.0 9.0 6.0
6.5 12.0 7.0 8.5 10.5 4.5 5.0 11.0 8.0 9.0 8.5 11.0 13.5 12.0 17.0 16.0
20.5 18.0 10.0 4.0 7.0 8.0 7.5 7.0 9.0 9.0 8.5 9.5 11.0 6.0 16.0 8.0
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8.0 35.0 13.0 3.0 4.0 2.5 -3.0 6.5 8.5 10.0 8.0 10.0 9.0 11.0 12.0 6.5
10.0 8.5 9.0 15.0 20.0 19.0 18.5 16.5 8.0 15.5 12.0 14.5 12.0 5.0 9.5 8.5
7.0 0.5 4.5 7.0 2.0 5.0 4.0 -2.0 4.0 6.0 8.0 12.0 10.5 6.5 7.5 32.0
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5.0 0 23.0 18.0 0 -3.0 7.0 12.0 12.0 7.5 0 8.0 4.0 7.5 7.0 4.0
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14.5 15.5 17.5 30.0 29.0 23.0 10.0 13.0 20.0 22.0 11.5 1.0 -6.0 -10.0 -12.0 -8.0
-4.0 2.0 14.5 6.0 2.5 4.5 5.0