C. 1

A COMPARISON OF COMPUTER-BASED TERRAIN STORAGE METHODS WITH RESPECT TO THE EVALUATION OF CERTAIN GEOMORPHOMETRIC MEASURES

by

DAVID MICHAEL MARK

B.A., Simon Fraser University, 1970

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

in the Department
of
Geography

We accept this thesis as conforming to
the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

February, 1974

Department of Geography

The University of British Columbia
Vancouver 8, Canada

Date March 11, 1974

Abstract

Topographic information can be digitized in several ways. Sampling may be surface-random (points selected according to partially or completely arbitrary criteria) or surface-specific (points selected according to their topographic significance). Surface-random sampling includes grids, contours, and randomly-located points. In this study, grid sampling and surface-specific sampling are compared. Surface behavior between sampled points is assumed to be linear.

All aspects of surface form can be considered to reflect surface roughness. Horizontal variation includes the concepts of texture and grain, while vertical variation is discussed under relief. The relationships between these are embodied in slope and the dispersion of slope magnitude and orientation. The distribution of mass within the elevation range of a topographic surface is described under hypsometry. Parameters for investigation are selected from these categories.

The variation of some selected geomorphometric parameters in southern British Columbia is examined via a stratified random sample consisting of forty-two 7 x 7 km areas. The values of some of these parameters are used to group the samples, and six are chosen for more detailed analysis. The relationships among the variables are examined using correlation analysis.

For four geomorphometric measures (local relief, mean slope, roughness factor, and hypsometric integral), the theoretical errors involved in estimating the measures from the two selected terrain storage methods are discussed. The surface-specific point samples should produce better results than grids of reasonable densities. The latter, however, should require less digitization time and computer storage space per point. For at least local relief and hypsometric integral, grid error should be a linear function of grid spacing.

Results of empirical comparison of the methods over the six selected areas are presented. The average surface-specific point data set is found to require some 2.6 times as much digitization time and 3.1 times as much computer storage space as the 15 by 15 grids used in the comparison. Computed estimates obtained from both of these data bases are presented for each of the four selected parameters, together with other estimates (obtained manually) in some cases. The average errors for the methods are found to differ significantly for local relief and mean slope but not for the hypsometric integral; for all three measures, the grids produce larger mean errors. The assumption of a linear relationship between grid spacing and grid error is used to estimate the grid spacing which would be required to produce the same average error as the surface-specific points. For the three parameters used, these hypothetical grids are calculated to require more computer storage space and digitization time than the surface-specific point data sets.

The influence of the density of surface-specific points and of base map scale appear to be related to the topographic texture. For a reasonably experienced terrain analyst, the reproduceability of these data sets appears to be good, although there remains a subjective element in point selection not present for grids. It is concluded that for a given amount of digitization time or computer storage space, better estimates of geomorphometric parameters can be obtained using sets of surface-specific points than using regular grids.

Table of Contents

List of Tables | Page

List of Figures | Page

Preface

When the current project was begun, it was the writer's intention to develop a computer system for the analysis and classification of terrain from topographic map data, with the specific aim of eventually producing a quantitative physiographic map of British Columbia. Some theoretical and empirical analyses (reported herein in Chapter 5) revealed that estimating geomorphometric parameters from a regular grid could introduce considerable error. The thesis objective was therefore redefined to become an investigation of the relative merits of grids and of alternative computer terrain storage systems. The results may be considered to represent a pilot study for the eventual realization of the original objective.

Throughout this study, the writer has benefitted greatly from discussions with his thesis supervisor, Michael Church. He and J. Ross Mackay read and commented upon drafts of the entire thesis, while Thomas K. Peucker has reviewed certain sections. Michael C. Roberts and H. Olav Slaymaker have also provided helpful advice. Financial support was primarily provided by the Department of Geography, University of British Columbia, in the form of Teaching Assistantships. Some support was also obtained from the "Geographical Data Structure" project, Geographical Branch, Office of Naval Research, Project NONR 710-100, principal investigator Thomas K. Peucker, Department of Geography, Simon Fraser University. Computer time was provided through the Department of Geography, University of British Columbia.

Chapter 1: Introduction

Geomorphometry, which has been defined by Chorley *et al.* (1957, p. 138) as the science "which treats the geometry of the landscape," attempts to describe quantitatively the form of the land surface; it is a sub-discipline of geomorphology. Evans (1972, p. 18) distinguished *specific* geomorphometry, which measures the geometry of specific types of landforms (see for example the work of Troeh, 1964, 1965, on "landform equations"), from *general* geomorphometry, "the measurement and analysis of those characteristics of landforms which are applicable to any continuous rough surface." In much of the geomorphometric literature, it has been claimed that the drainage basin represents "the fundamental geomorphic unit" (notably Chorley, 1969; see also Leopold *et al.*, 1964; Williams, 1966). This view was taken to an extreme by Connelly (1968), who in a discussion of terrain statistics stated that "although it is an oversimplification it is certainly a valid approximation to attribute all land forms to the fluvial erosion of uplifted rock masses" (p. 78). He stated that this assumption was necessary in order to develop "a unified framework for landscape geometry." Since about one third of the earth's land surface was glaciated during the Pleistocene (*cf.* Flint, 1971, p. 19), and as other processes such as fluvial deposition, or aeolian, volcanic, or periglacial action have also influenced large areas, it is the writer's opinion that a "unified framework" could only be produced if *no* single process is assumed. Furthermore, the specific approach can only be applied once an area of the earth's surface has been identified as a drainage basin, an alluvial fan, a drumlin, *et cetera*.

The object of this study is to investigate the use of computer-stored topographic information in the evaluation of geomorphometric parameters. Computers have been widely employed in both geography and the earth sciences, and geomorphology has not been an exception. A recent book edited by Chorley

(1972) attests to the fact that spatial aspects of land surface form have received much attention. While computers have been used in geomorphometry, there have been few attempts to store topographic surfaces in computers and then to perform detailed quantitative analyses of land surface form. Exceptions are the works of Hormann (1969, 1971), who approximated land surfaces with sets of contiguous triangles, and of Evans (1972), whose work was based on regular square grids ("altitude matrices"). Neither of these works studied the comparative accuracy, precision, and efficiency of computer terrain storage methods, the differences between computer estimates and "standard" methods for estimating geomorphometric measures, or the relative digitization (data gathering) times and computer storage requirements. It is the purpose of this study to review various computer terrain storage systems, and to compare the triangle and grid methods noted above. The comparison will be based on the estimation of a group of landform parameters selected after a review of many such measures. For the reasons cited above, emphasis will be placed upon general geomorphometric parameters, although some attention will be directed toward measures based specifically upon landforms of fluvial activity, probably the most important single class of processes which has shaped the earth's surface. All examples used in the comparisons will be drawn from topographic maps of that part of British Columbia which lies south of 54 degrees latitude, mostly from 1:50,000 scale maps. Since all topographic data used in this study will be derived from contour maps, it seems in order to discuss briefly the precision of topographic map information.

1.1: Precision of Topographic Map Data

Boesch and Kishomoto (1966) expressed elevation errors in terms of root-mean-square errors, herein designated s_e. For example, they stated that survey s_e values for triangulation points are generally less than 0.5 m horizontally and 0.1 m vertically (pp. 9-10), while root-mean-square errors in map plotting range from 0.01 to 0.3 mm on the map (p. 12). For a 1:50,000 scale map, this would represent 0.5 to 15 metres on the ground. Boesch and Kishomoto stated that contour precision has two aspects: "(1) the positional error of a point on a contour, and (2) the height error of a point whose elevation is determined (or read) from the nearest contours by interpolation" (p. 14). They presented a graph of allowable standard deviations in metres as functions of ground slope for various countries and map scales (their Figure 2).

Thompson and Davey (1953, p. 40) cited the accuracy specifications of United States Geological Survey topographic maps as:

> Vertical accuracy, applied to contour maps on all publication scales, shall be such that not more than 10 per cent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.

They used the 90 per cent criterion in conjunction with a table of ordinates of the normal curve to estimate the allowable s_e value as about 0.3 times the contour interval. The conversion of horizontal errors into vertical ones involves the tangent of ground slope.

Standards for Canadian topographic maps do not appear to be as well defined. W.A. Williamson (pers. written comm., 1972) stated that the Canadian Surveys and Mapping Branch designs its maps so that "on Class A maps the contours are accurate to one-half a contour interval." If it is assumed that this represents a 95 per cent confidence level, the ordinates of the normal curve can be used to estimate the allowable root-mean-square height error as 0.255 times the contour interval. Williamson also stated that for Canadian Class A maps, points are to appear within 0.5 mm of their true positions as map scale -- this would represent 25 m on the ground for 1:50,000 scale maps.

Following Thompson and Davey's (1954, p. 43) approach, but using this scale and a 100-foot (30.5 m) contour interval, the root-mean-square error for the maps used in this study should be given by:

$$s_e = \pm (7.8 + 25.0 \tan \delta) \text{ metres} \qquad (1.1)$$

where δ is the ground slope.

Another possible source of contour error is the generalization required when smaller scale maps are compiled from larger scale ones. Pannekoek (1962) discussed this, and stated that in some cases, contours should be "moved aside" in some valleys or along coasts in order to "make room" for cultural features such as roads and railways. This should not be a factor in the present study, as the map series used herein is now compiled "at publication scale" (Williamson, pers. comm.), and was formerly compiled for only a 20 per cent reduction.

Errors or inconsistencies in the portrayal of the drainage net on maps may present problems in estimating drainage parameters. This problem has received more attention than has the precision of relief estimates (c.f. Morisawa, 1957; Giusti and Schneider, 1965; Eyles, 1966; Gregory, 1966a, 1966b; McCoy, 1971). Most of these writers found that the "extended drainage network", that is, the network formed by extending streams along contour crenulations, was more closely related to the drainage net determined in the field or from aerial photographs than was the "blue line network" printed on the maps (see Morisawa, 1957; Eyles, 1966). Other authors (notably Gregory) argued that the use of the extended network might lead to the inclusion of former channels not now part of the drainage system, such as "dry valleys" in karst areas or former glacial meltwater channels. Because drainage net parameters do not form an important part of the present study, analysis will be simplified through the use of the "blue line" stream network shown on the topographic maps.

1.2: Notation

Throughout this paper, terms and symbols are defined where they are first introduced. In addition, a complete listing of all symbols used will be given in Appendix I. Where there are "standard" symbols for variables, these will be used unless ambiguity would result. Furthermore, x and y are reserved to indicate geographical location, z elevation above sea level, N a number of objects or occurrences, D a density value, r a correlation coefficient, and s a root-mean-square value. The metric system of units is employed throughout, with British units being given in some instances. Elevations obtained from the maps were in feet, but were converted to metres before analysis.

Chapter 2: Computer Terrain Storage Systems

Topography can be considered to be a continuous surface, and thus even a small area contains an infinite number of points; the number of points which can be measured is limited by the resolving power of one's instruments and not by the surface itself. Since it is generally not possible to specify the land surface completely, the usual objective of computer terrain storage systems is to obtain a "satisfactory" representation of the surface which will minimize both the effort required to obtain the data and the computer storage requirements, while at the same time maximizing the efficiency with which some particular type of processing may be performed. In the present study, the "processing" involves the estimation of some geomorphometric parameters. The problem is really two-fold: one aspect involves the collection of topographic information from maps or other sources, while the second relates to the storage, retrieval, and processing methods employed.

2.1: Digitization

Digitization can be defined as the process by which "analog measures", such as length or location on a map, are converted into "digital, computer-usable form" (Peucker, 1972, p.72). Two distinct digitization strategies are available: one involves sampling at surface-random points or lines, while the other uses surface-specific points or lines. In the surface-random approach, the points sampled are not selected on the basis of surface form but according to some partially or completely arbitrary set of criteria. Randomly-located points are obviously surface-random, but points selected using equal increments in the x- and y-directions (grid sampling) or equal increments in elevation (contours) are also generally random with respect to the surface. When surface-specific points or lines are used, knowledge of the form of the surface being sampled (usually obtained by a visual inspection of a contour map or of the land surface itself) is used to select points or lines which contain a maximum amount of information. These include peaks and pits, passes, ridges and course lines, and breaks of slope.

2.2: Surface-random Sampling: Grids

The most widely used method for storing and processing three-dimensional surfaces is probably the square grid, also known as the "altitude matrix" (Evans, 1972, p. 24), or as "both a digital terrain model and a numerical map" (Connelly, 1972, p. 92). Sample points are located at the intersections of two orthogonal sets of regularly-spaced parallel lines. Only the altitude of the surface at each sample point must be measured and stored within the computer -- the geographical locations are determined by the grid spacing, and are implicit in the sequential position of the altitude value within the computer storage array. A wide variety of computer programs for the processing of gridded data is available. Another advantage lies in the fact that the neighbours of a given data point, which are often required in the calculation of geomorphometric parameters, can be readily obtained, once again from the positions of points within the computer array.

The principal disadvantage of the regular grid is its tendency toward redundancy -- the grid must be made sufficiently dense throughout to portray the smallest objects which must be shown anywhere within the area covered by the grid. According to Tobler (1969, p. 243), the sampling theorem states that "if a function has no spectral components of frequency higher than W, then the value of the function is completely determined by a knowledge of its values at points spaced 1/2 W apart." Thus a regular grid with a grid spacing *d* can only be expected to depict those variations of the surface having wavelengths of 2d or more. If the smallest significant wavelength of object one wishes to detect or portray *anywhere* within a study area is of size ("wavelength") *S*, then the grid spacing *everywhere* must be 1/2 S or less. "Smoother" sub-areas of the study area will then contain far more points than are needed to portray their form. To improve the "resolution" of a grid by a factor $\underline{f}$, the grid spacing must be decreased by this factor -- the total number of data points is increased by a factor of f^2.

Tobler and Davis (1968) described a number of regular grid data sets of various types of terrain which together form a "digital terrain library". Because of the wide application of this terrain storage method, the larger number of gridded terrain samples already collected, and the number of computer programs available, this method will be examined intensively in later chapters.

At least two other grid approaches have been used: one is a "regular triangular grid", while the other was termed the "variable grid" method by Boehm (1967, p. 404). The regular triangular grid has some advantages over the square grid approach. Each point has six neighbours which form a regular hexagon, and Mackay (1953) discussed how this form of data collection avoids the "saddle point problem" which sometimes arises in attempting to draw isopleths based on a square grid. The advantage in this regard is probably outweighed by the increased complexity involved in indicating geographical location implicitly in the computer storage allocation. Most of the drawbacks of the regular square grid would also apply to a regular triangular one.

In the variable grid method, a "master" regular grid is used, but in rougher areas, denser regular grids are applied; the redundancy of the denser grid in smoother parts of the surface is thus avoided. Some preliminary analysis would be required to determine the areas in which a denser grid should be used, and how dense it should be. If the smallest significant terrain wavelength within each sub-area can be estimated, the sampling theorem discussed above can be used to determine the required grid spacing. This implies some knowledge of the surface form before the data are collected, and thus the variable grid method is not completely "surface-random", although the exact locations of the data points remain so.

There is some disagreement as to the relative merits of completely random sampling of a surface, in which the locations of the sample points are random, and of the type of "surface-random" sampling represented by regular grids. Strahler (1956, p. 589-592) considered the "random co-ordinate method" and the regular grid for sampling surface slope. He stated that:

> "It might be supposed that a regularly distributed sample would give coverage more uniformly representative of the entire area and would be superior to the random co-ordinate method. According to statistical principles, however, this grid sample is unsatisfactory because variance cannot be computed simply." (p. 591)

Since even the regular grid points are random with respect to such surface characteristics as elevation and slope, the writer cannot understand why the variance of slopes for 100 gridded points cannot be determined in exactly the same way as for 100 randomly-located ones. Strahler also noted that the grid might produce a systematically-biased sample if the grid lines happen to be aligned parallel to linear features in the topography, such as ridges or valleys. This latter argument was also put forward by Haan and Johnson (1966, p. 124) with reference to the sampling of elevations to be used in the construction of hypsometric curves. Because of their inherently uneven distribution, however, randomly-located points might also produce biased sampling, although the bias will not be systematic -- there will simply be more data points in some parts of the study area than in others.

W.D. Rase (personal oral comm., 1970; pers. written comm., 1973) investigated the relative "information contents" of randomly-located and gridded elevation samples; this unpublished study represents the only quantitative comparison known to the writer. Three surfaces were first represented by 150 x 150 grids; the surfaces were a plane, a fourth-order polynomial, and a 23.7 km square topographic sample from the Lake Louise 1:50,000 scale map sheet (grid spacing about 160 m). Samples of between about 100 and 500 points were taken from each of these populations of 22,500 points in three ways -- random, "systematic stratified aligned" (regular grid), and "systematic stratified unaligned" in which the rows and columns of the grid were not aligned with the co-ordinate axes. 50 x 50 grids (2,500 points) were then interpolated from these samples using the SYMAP program (see section 2.5), and these were compared with the corresponding points from the original data sets using various simple statistical measures. Figure 2.1 plots the coefficient of determination against sample size for each of the nine cases examined by Rase. For each surface, the two systematic approaches (grids) produced considerably better results than the random co-ordinate method; the aligned samples tended to give somewhat better results than the unaligned systematic samples. This evidence strongly suggests that grid samples provide a "better" representation of a surface than do random co-ordinate samples, and appears to refute the unsubstantiated claims of Strahler (1956) and Haan and Johnson (1966). Of course, the actual values of the coefficients of determination shown in Figure 2.1 are at least in part dependent upon the particular interpolation model chosen to generate the 50 x 50 grids (see section 2.5). Furthermore, the problem investigated by Rase was not the same as those investigated by the other authors.

From the point of view of computer storage, the random co-ordinate approach would have the added disadvantage that all three co-ordinates of each point must be specified and stored -- the advantages of implicit geographical location and implicit neighbours which hold true for grids are lost.

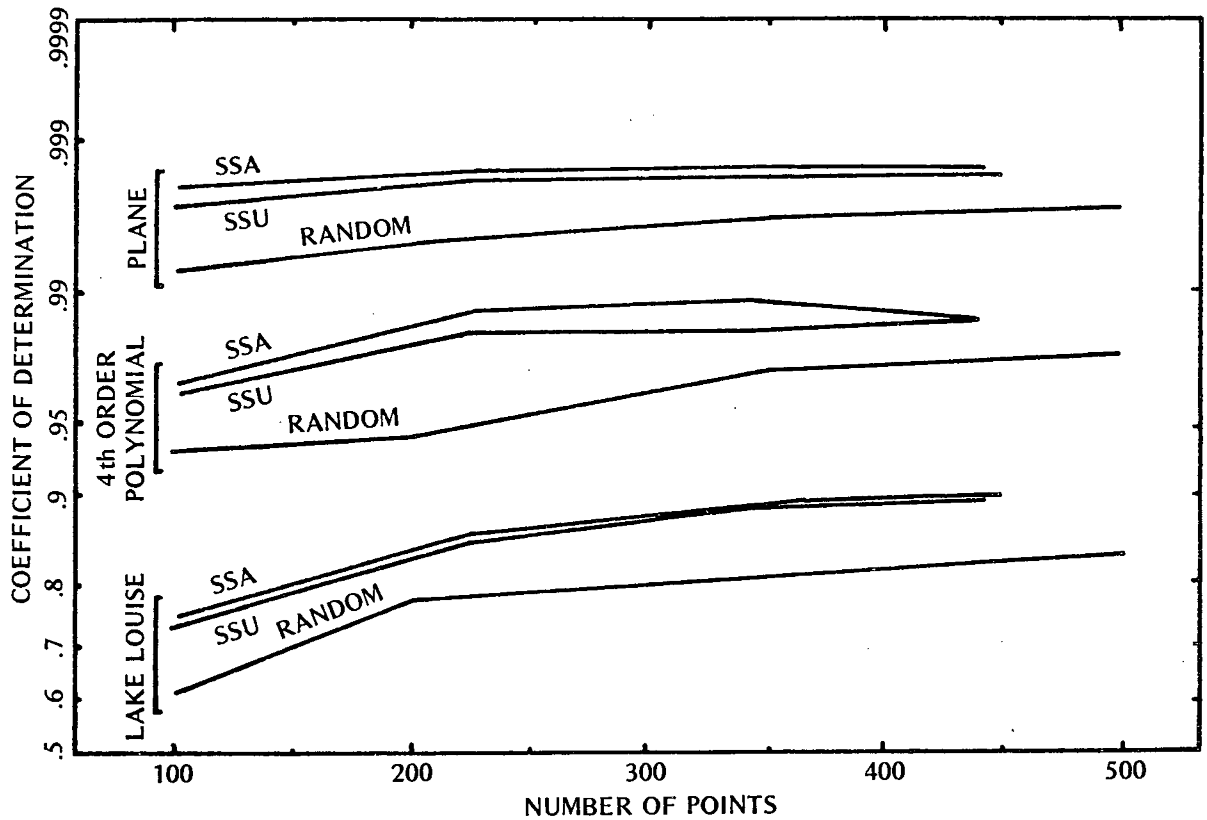


Figure 2.1: Coefficients of determination as functions of sample size for three sampling designs (random, systematic stratified unaligned, systematic stratified aligned) applied to three surfaces of varying complexity (after W.D. Rase, unpublished study).

2.3: Surface-random Sampling: Digitized Contours

Contours represent another way of sampling and storing a terrain surface. It must be noted that the elevations of the contours are fixed by sea level (or other datum) and the contour interval, and are thus random with respect to surface features. On some maps, supplementary contours or spot elevations are used to provide the map user with additional information. The storage of topography through the use of digitized contours is of particular interest in light of recent developments in automated compiling and drafting of topographic maps. As the contours are determined using stereoplotters and plotted automatically, the succession of points along the contours could readily be stored on tape and made available for geomorphometric processing. Evans (1972, p. 23-27) discussed the relative merits of digitized contours and of altitude matrices. He noted that while the former method is superior if one wishes to know the locations of all pints of a certain height, it is inferior if one wishes to know the elevation at a given location. Since the latter sort of question arises much more often in geomorphometric snalysis than the former, it would seem that digitized contours are less suitable for geomorphometric analysis than are regular grids. More storage space is required per point, since only the elevation can be indicated implicitly, and two values per point must be explicitly stored. Boehm (1967) described a "contour tree ordering method" for storing surface information; this method is said to be more efficient in problems where "successive specified points are correlated, such as in line-of-sight calculations" (p. 405) than would be a storage of contour points sorted by x co-ordinates. Boehm's work will be discussed further in section 2.7.

Computer programs are available for determining slope steepness and aspect directly from contour data (see section 3.4.2); routines for producing contours from grids are widely available, and the inverse process, that is, producing grids from digitized contour data, is also possible. These processes would both involve interpolation, and the choice of the interpolation model (section 2.5) would influence the results.

2.4: Surface-specific Sampling: Points and Lines

Surface-specific points can be defined as "points which furnish more information about the surface than only their co-ordinates" (Peucker, 1972, p. 23). These were termed "significant topographic points" by Hardy (1971, p. 1907). Surface-specific points include peaks and pits (maxima and minima, respectively, on the surface), passes or saddle points, stream and ridge junctions, and points where there are significant changes in the directional trends of surface-specific lines. (See Figure 2.2.) These lines include ridges, course lines, and breaks of slope. There has been some work on the relationships among and links between various types of surface-specific points and lines on continuous, continuously-differentiable surfaces. This was begun by Cayley (1859) and Maxwell (1870), and revived by Warntz (1966, 1968). Since both Peucker (1972, p. 24) and Woldenberg (1972, p. 327-330) have recently reviewed this work and as it is not directly relevant to the current research, no summary will be included herein.

The writer knows of no work on the relative "information contents" of surface-specific and surface-random points; Peucker (1972, p. 72), however, claimed that "surface-specific points have a higher information content than surface-random points." Fewer of these should be required to define a surface to a given level of precision, but there is no evidence to suggest how many fewer.

Surface specific points require more storage space and digitizing time than do an equivalent number of grid points, since all three co-ordinates must be explicitly determined and stored. There is an element of subjectivity in the selection of surface-specific points and, furthermore, neighbours cannot easily be determined from the points alone.

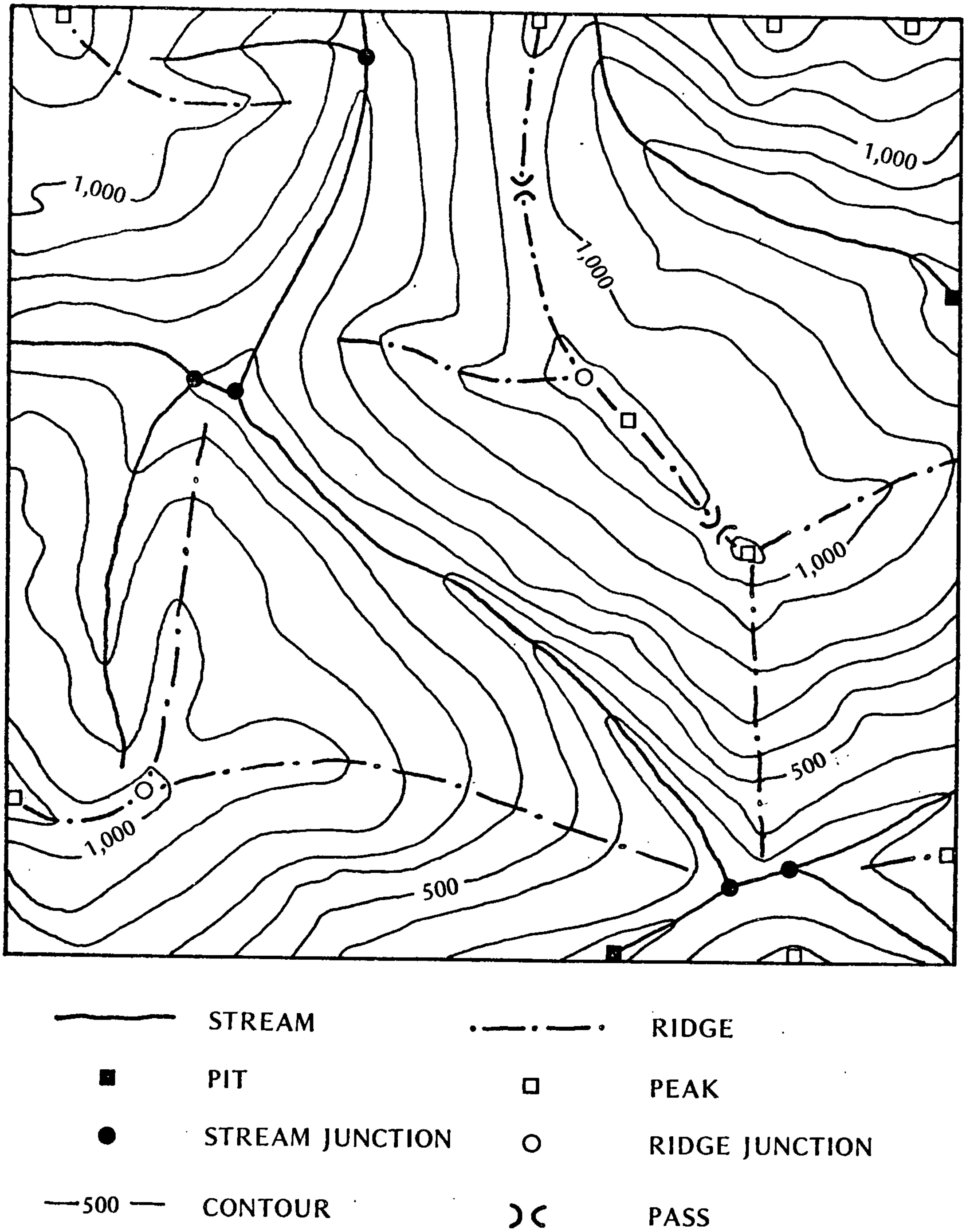


Figure 2.2: Map to illustrate types of surface-specific points and lines.

2.5: Surface Behavior

However the sample points are chosen, one must make some assumptions about the behavior of the surface between the data points. Sometimes these assumptions are based on a theoretical or empirical knowledge of the actual surface behavior, but more often they are arbitrary. In this study only interpolating surfaces, *i.e.*, surfaces which pass through all the data points, will be considered; approximating surfaces (known as trend surfaces), which do not necessarily pass through all the points and which are thus "smoother" than the original data, have also been applied to topography. These works have mainly been involved with attempts to determine the forms of former "erosion surfaces" now represented only by hilltops (*cf.* King, 1969; Monmonier, 1969; Rodda, 1970; Tarrant, 1970). Bassett and Chorley (1971) computed trend surfaces based on 15 x 15 grids of terrain elevations in an attempt to determine different scales of variation of the topography. Such work, while interesting, is beyond the scope of the present study.

As mentioned above, interpolation usually involves an arbitrary assumption about the behavior of the surface between data points. Robinson (1960, p. 186-7) stated the "standard" cartographic assumption that, in determining the positions of isarithms from control points, linear interpolation should be used "when no evidence exists to indicate a nonlinear gradient between control points." Peucker (1972, p. 25) noted that linear interpolation, in particular the representation of a surface by a contiguous non-overlapping set of triangular planes, "represents the simplest, fastest, and often the least misleading interpolation method." Peucker goes on to point out, however, that such surfaces have discontinuities in the first derivative (*i.e.*, have "breaks of slope") which may produce an "unpleasant" appearance in block diagrams or contour maps. Perhaps for this reason, most computer algorithms for producing dense regular grids from a less dense sample of points, (e.g. UBC XPAND; SYMAP) use an inverse-distance-squared weighted average of the heights of a number of surrounding data points. Since distance is determined using Pythagoras' Theorem, use of the squared distance in weighting elevations eliminates the need for a square-root determination, reducing computer processing time. A surface thus produced is continuous in the first derivative and therefore appears "smooth". A general interpolation formula may be expressed as:

$$z_i = \sum_j \frac{z_j}{c_{ij}^{\beta}} \Big/ \sum_j \frac{1}{c_{ij}^{\beta}} \qquad (2.1)$$

where z_i is the height to be determined, the z_j the elevations of neighbouring points, and c_{ij} the distance between points i and j. For linear interpolation, $\beta = 1$, while in the more common interpolation algorithms discussed above, $\beta = 2$. There has been little if any research into the effect of β-values on surface behavior; Figure 2.3 illustrates the influence of these values on the form of a surface between data points. This diagram suggests that different β-values may be appropriate for different types of terrain. In the absence of any work on optimal β-values, the linear assumption, i.e., a β-value of one, will be used in this study.

If data are in a square grid, triangular planar facets for determining slope or other parameters can be produced in two different ways. In one approach, one set of diagonals is arbitrarily inserted. Turner and Miles (1967, p. 260) determined a roughness parameter for the two orientations of diagonals and found very little difference in the results. Alternatively, additional points in the centres of the grid squares may be interpolated by averaging the four surrounding points and used to form triangles. This is done in some contouring programs in order to avoid the "saddle point problem" discussed in section 2.2.

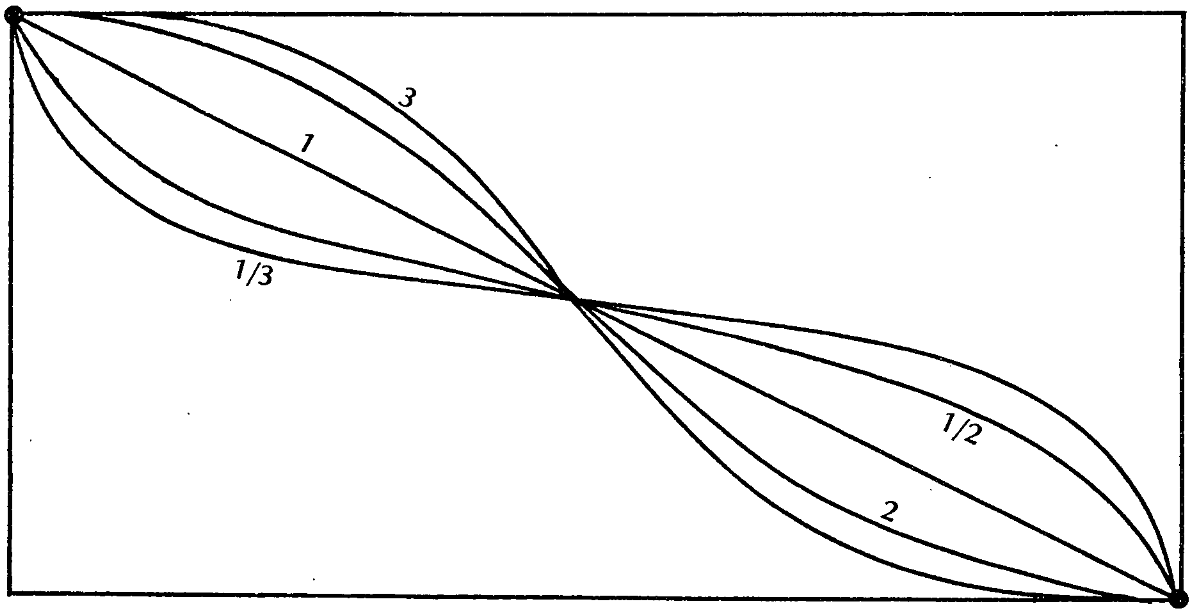


Figure 2.3: Form of the interpolated surface between two data points (circles) for various exponents in the general interpolation formula (see equation 2.1).

2.6: Computer Storage of Terrain Information

There are a number of possible approaches to the storage of numerical terrain information. Most simply, the data may be stored directly, as a matrix of elevations for gridded data, as lists of x and y co-ordinates for digitized contours, or as all three co-ordinates for surface-specific points. The surface between the points would then be determined during the processing stage after retrieval. In the case of irregularly-distributed points such as surface-specific points, however, processing will be much more efficient if the neighbours of each point are indicated in some way -- as already noted above, this is not required for gridded data. This can be achieved in at least two ways. Hormann (1969, 1971) stored the identification number and co-ordinates for each point. He then listed all the neighbours (by identification number) for some arbitrarily-chosen starting point. Next, for each of these neighbours, all adjacent points excluding the starting point are given, and the procedure is continued until every link between neighbours has been included exactly once. During processing, the computer forms triangles, beginning at the arbitrary starting point. If all neighbours of any particular point other than the first one are required, all previous pointer lists would have to be searched. In the basic storage system of the Geographical Data Structure[1] (GDS), all neighbours of every point are included in that point's pointer list, making it easier to find any point's neighbours. This makes searching through the data structure easier than in Hormann's version but requires more storage space as each link appears in two pointer lists. This storage method is herein termed the "pointer mode" of the GDS.

---

1 Geography Branch, Office of Naval Research, Task No. 710-100, Department of Geography, Simon Fraser University, Burnaby, British Columbia, T.K. Peucker, principal investigator

Another approach is to store the point numbers and co-ordinates, and then to store a list of triangles, each record containing the triangle number and the identification numbers of the three points making up its vertices -- this is termed the "triangle mode" of storage. Other characteristics of the triangle could also be indicated. This form of data organization is somewhat easier to prepare, and is also more efficient for "triangle-by-triangle" processing required for most geomorphometric analysis. The triangle mode was used by Akin (1971), with elevations replaced by precipitation values, in the calculation of the mean areal depth of precipitation. The triangle mode should be far less efficient for searching through the data structure than would be the pointer mode; computer routines for producing one data structure mode from the other are currently being developed under the GDS project. The project is also developing methods for determining the neighbours of a set of surface-specific points given only the points' co-ordinates.

It is possible to produce a regular grid from a set of surface-specific points by interpolation (equation 2.1). The results will be influenced by the choice of the β-value; the appropriateness of the β-value of 2 used in most interpolation algorithms is suspect.

Yet another approach to numerical terrain storage is to find an explicit mathematical function or set of functions which either interpolate or approximate the surface. The coefficients of the equations, rather than the points themselves, would be stored, and could be based on gridded or non-gridded data. Such equations can usually be differentiated, the results being equations of surface slope over the area. If a constant elevation is subtracted from the equation, the root of the resulting equation will give the contour of that elevation. Junkins and Jancaitis (1971) found that this approach was an order of magnitude more efficient than the method of evaluating the surface equation at a large number of grid points and then using "standard" grid contouring methods. The latter approach was used in the same context by Hardy (1971, 1972). The functions can also be integrated over the study area to determine the volume under the surface, which is of geomorphometric interest. Once again, however, there are often arbitrary assumptions about surface behavior; also, Hardy's method requires that the data points and one coefficient per point be stored, resulting in little saving of storage space, although processing may be speeded up.

2.7: Comparisons of Approaches

Boehm (1967) compared five methods of surface storage: contour points sorted in the x-direction (CS), "contour tree ordering" (CT), uniform grid (UG), uniform grid-differential altitude (UGDA), and variable grid-differential altitude (VG). "Differential altitude" means that altitude differences between neighbours rather than absolute altitudes are stored. Boehm presented an extensive table (his Table II, p. 410) of "performance estimates" for the various methods. He then applied them to a problem in intervisibility between points on the surface, determining both storage requirements and processing speed. The grids were most efficient in terms of processing speed, with the uniform grid the best, while the variable grid required the least storage. Some other comparisons of methods have already been cited above.

2.8: Conclusions

As Boehm (1967, p. 414) stated, "one cannot discuss the relative efficiencies of tabular representation methods without reference to the problem being solved." Thus the results of studies by Rase (see Figure 2.1) and Boehm (see above) are not directly applicable to the problem considered here, that is, the estimation of some selected geomorphometric parameters. These parameters will be selected after a review of many such measures in the next chapter. The terrain sampling and storage methods compared will be the regular grid (altitude matrix) and an approach based on surface-specific points. The regular grid is representative of various methods of surface-random sampling, and these two approaches are the only computer terrain storage systems which have been applied to problems of general geomorphometry (cf. Evans, 1972; Hormann, 1969, 1971). As noted above, surface behavior between data points will in both cases be assumed to be linear.

Chapter 3: Geomorphometric Parameter

In this chapter, an attempt will be made to review a considerable number of geomorphometric parameters in such a way as to produce a rational classification of these measures. Attention will be focussed upon two points: the amenability of the parameters to measurement based upon the computer terrain storage systems discussed above, and the probable geomorphic significance of the measures. No attempt will be made to review papers approaching landscape analysis through a set of landform "elements", "units", or "facets" (examples of this approach include: Van Lopik and Kolb, 1959; Lebedev, 1961; Conacher, 1968; Speight, 1968; Thomas, 1969; Wong, 1969; Gerenchuk *et al.*, 1970) . In cases where the units were based upon quantitative landform parameters (*e.g.* Speight, 1968), only the parameters will be discussed. Similarly, graphical analysis methods will be reviewed only where they are related to important geomorphometric parameters.

Chorley (1969, p. 78) proposed that characteristics of drainage basins and drainage nets could be divided into geometrical properties, which involve the relationships among dimensional properties such as elevations, lengths, areas, and volumes, and *topological* properties which relate numbers of objects in the drainage net (for example, the bifurcation ratio). The latter properties will not be considered herein.

All measures of land surface form can be considered to be in some way representative of the "roughness" of the surface. This discussion will thus begin with a discussion of the general concept of roughness before proceeding to actual geomorphometric parameters.

3.1: The Concept of "Roughness"

In a general sense, roughness refers to the irregularity of a topographic surface. Stone and Dugundji (1965) and Hobson (1967) observed that roughness cannot be completely defined by any single measure, but must be represented by a "roughness vector" or set of parameters. One area may be rougher than another because it has a shorter characteristic wavelength (finer grain or texture), a higher amplitude (relief), an irregularity of ridge spacing, or sharper ridges (see Figure 3.1). Stone and Dugundji, in a study of microrelief profiles, used five measures, while Hobson computed 9 other measures based on three different "roughness concepts".

It is convenient to discuss terrain roughness by analogy with combinations of periodic functions or spectra of the terrain. Evans (1972, p. 33-36) reviewed some of the attempts to analyze topography using spectral analysis explicitly. He observed (p. 36) that in practice this has not been very successful, because valleys often curve, and they converge downstream, while valley spacing within an area is seldom regular. The general ideas of wavelength and amplitude are useful, however, and geomorphometric measures will be discussed in this context. The significant wavelengths of the topography are termed grain or texture, while the amplitudes associated with these wavelengths correspond to the concept of relief. The relationship between the horizontal and vertical dimensions of the topography is embodied in the land slope and the dispersion of slope magnitude and orientation, while the vertical distribution of mass under the topographic surface is contained in the concept of hypsometry.

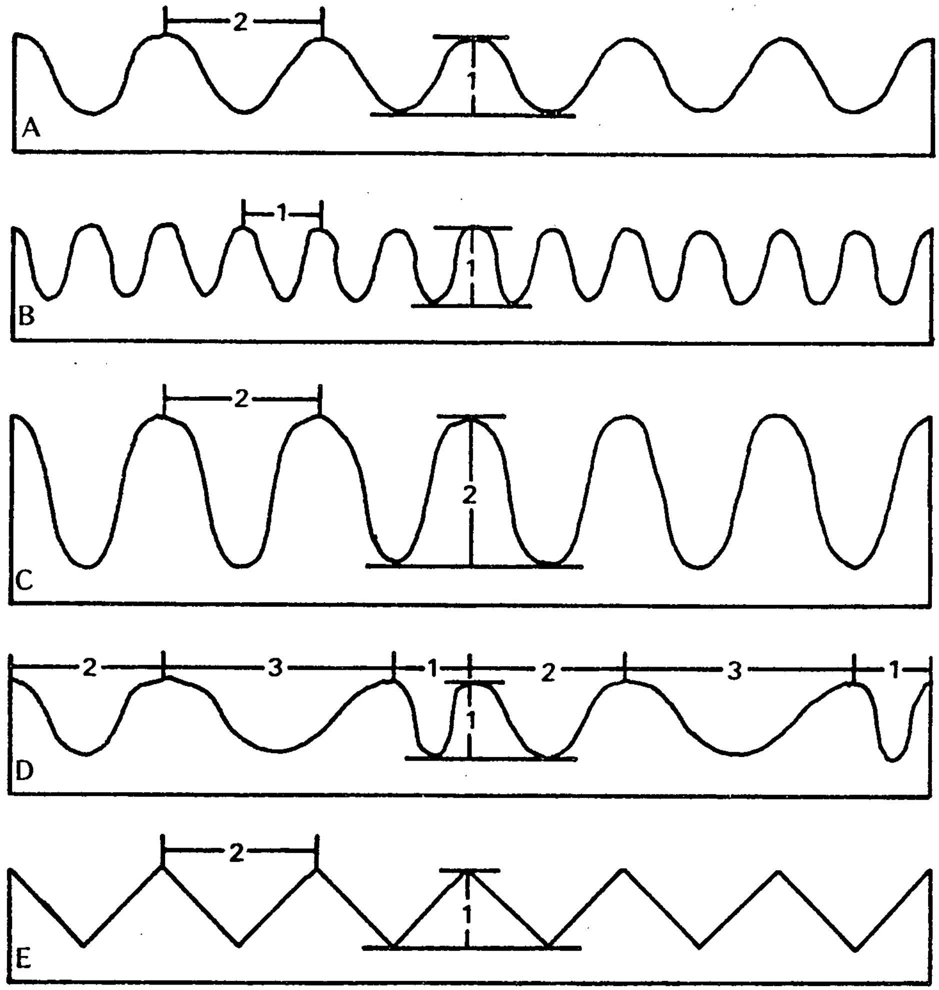


Figure 3.1: Forms of surface roughness. B, C, D, and E are "rougher" than A in some respect. B has a shorter wavelength, C a higher amplitude, D an irregularity in spacing, and E a "sharper" form.

3.2: Texture and Grain

Texture and grain are terms which have been used to indicate in some way the scale of horizontal variations in the topography. These terms have been used in different contexts, and this difference is preserved if texture is used to refer to the shortest significant wavelength in the topography and grain used for the longest significant wavelength. Texture is related to the smallest landform elements one wishes to detect, and grain to the size of area over which one measures other parameters.

3.2.1: Grain

Wood and Snall (1960, p. 1) defined grain as "the size of area over which the other factors are to be measured. It is dependent on the spacing of major ridges and valleys and thus indicates texture of topography." Grain was calculated by determining the local relief within concentric circles around a randomly-located point. Relief was plotted against diameter and, according to the authors, there will generally be a "knick point" in this curve -- the diameter at this knick point will be the grain (G). Wood and Snell used diameter increments of one mile, and suggested that if there is no knick point, relief values for the diemeters of circles centred at a number of points should be determined and averaged; "this technique will produce a definite knick point so that no doubt remains as to the grain size " (p.5). They (p.6) noted that the method is not very precise, but believed that it was better than measuring parameters such as relief for a standard arbitrary area. In the present study, "grain" is also used less formally to refer to the longest significant topographic wavelength. Other parameters should be sampled over areas larger than or equal to the grain size in order to obtain representative values.

3.2.2: Texture

As noted above, the term texture is herein applied in a general sense to refer to the shortest significant topographic wavelength. This should determine the grid spacing for grid sampling or the size of the triangles for surface-specific point sampling. The word "texture" has been used for a specific geomorphometric parameter. Smith (1950) proposed a texture ratio:

$$T = N/P \qquad (3.1)$$

where "N is the number of crenulations on the selected contour, and P is the length of the perimeter of the basin given in miles or fractions thereof" (p. 657). He "selected" the contour having the most crenulations. Smith found that the texture ratio was closely related to drainage density (see below, section 3.2.3) by the following empirical relationship:

$$D_d = 1.658\, T^{1.115} \qquad (3.2)$$

Smith did not give confidence limits for the regression coefficients, but the closeness of the exponent to one suggests to the writer that the relationship may in fact be linear. The nearly linear relationship between T and the drainage density is not surprising, since the inverse of T is closely related to the average distance between contour crenulations along the selected contour. As each crenulation represents a stream in the "extended drainage network", the inverse of T is closely related to the mean distance between channels, which is in turn the inverse of drainage density.

3.2.3: Drainage Density (Dd)

As already noted, drainage density is closely related to texture. Drainage density, defined by Horton (1945, p. 283) as the total length of stream channels per unit area, represents a very important geomorphometric parameter. It has been found to be closely related to mean stream discharge (cf. Carlston, 1963), mean annual precipitation (cf. Chorley and Morgan, 1962), and sediment yield (Abrahams, 1972). It has also been shown to increase with time on till plains exposed by deglaciation (Ruhe, 1952). Roberts and Klingeman (1972) found that the total length of flowing channels at a particular time is closely related to instantaneous stream discharge. Thus drainage density for flowing channels only will vary over short periods of time. Evans (1972, p. 33) suggested that if only high order streams are considered, the inverse of valley density should provide a useful expression of overall topographic grain, since the inverse of drainage density is the mean orthogonal distance between channels.

In a method analogous to Wentworth's method for slope estimation (see section 3.4.1 below), Carlston and Langbein (unpub. 1960; cf. McCoy, 1971) and McCoy (1971) used traverse sampling to obtain a rapid estimate of drainage density (see section 4.3.4). Other writers have used the numbers of intersections between the drainage net and traverse lines directly without attempting to convert them to drainage density. Peltier (1962) plotted the number of drainageways per mile against mean slope and showed curves for a number of climatic or geomorphic regions; all traverse minima were counted, including closed depressions. Donahue (1972) determined "mean channel spacing" by counting intersections between the drainage net and a set of randomly-oriented traverse lines and dividing this into the total length of traverse. He did not, however, make a correction for the angle of intersection between traverse line and drainageway (see section 3.4.1). Wood and Snell (1957, 1959, 1960) determined a parameter called "slope direction changes", the total number of minima and maxima encountered along traverse lines of constant total length. Since the profile is continuous, maxima and minima must alternate, and the number of slope direction changes is twice the number of drainageways, plus or minus one. It would be possible to convert the data of Peltier, Donahue, and Wood and Snell to drainage densities for comparison with other studies.

Another parameter very closely related to drainage density is the source density (D_s), the number of stream sources per unit area (see Mather, 1972, p. 311). Both this and the preceding parameter are very sensitive to the portrayal of the drainage net. As already noted in section 1.1, there may be map-to-map inconsistencies in the portrayal of the drainage net, and for this reason some writers have used the "extended drainage network" formed by extending stress as indicated by the contour crenulations. This, however, introduces an element of subjectivity. The quality of the blue-line drainage net shown on some topographic map from southern British Columbia will be investigated in the next chapter.

3.2.4: Other Texture Measures

A different measure of surface texture is the number of closed hilltop contours per unit area, here termed the peak density (Dp). Wood and Snell (1959) used this as one of their parameters for classifying terrain. They considered any closed contour (other than a pit) to be a "hilltop". King (1966), in her application of factor analysis to geomorphometric measures, used two peak densities: "summit dissection", which was "the number of closed summit or spur contours" (p. 41), and "valley character", the number of closed valley contours, most of which represented drumlins. Swan (1967) mapped "hill frequency" as the density of hills per square mile. A hill was defined as any summit with two or more closed contours, or with a difference between top and base elevations of more than 50 feet (15.2 m). Using a related measure, Ronca and Green (1970) studied the density and distribution of craters on the lunar surface.

Yet another way of characterizing surface roughness is through an examination of ridges. Speight (1968) determined ridginess, the total length of ridge per unit area (analogous to drainage density) and reticulation, which was a measure of the size of "the largest connected network of crests that projected into a sample area" (p. 248). He also used modified two-dimensional vector anlysis on ridge segments to measure the degree to which the ridges tended to be parallel.

3.3: Relief Measures

The term relief is used to describe the vertical dimension or amplitude of topography. Evans (1972, p. 31-32) noted that the majority of relief measures depend upon the extreme values of the distribution of elevations, and would thus be sensitive to rather minor variations in estimations of these heights. He therefore proposed that the standard deviation of altitudes would provide a more stable measure of the vertical variability of the terrain. He did observe that "the autocorrelation of altitude admittedly makes range less unreliable than it is for random variables, since on a continuous surface all intermediate values between the extremes must be represented" (p. 31), but nevertheless recommended use of the standard deviation. All of the other papers reviewed herein have, however, used extreme values to characterize the vertical dimension.

3.3.1: Local Relief (H)

For any finite area of a surface, the local relief is defined as the difference between the highest and lowest elevations occurring within that area. It is important to note that local relief is always defined with respect to some particular area, and perhaps for this reason has sometimes been termed the "relative relief" (cf. Smith, 1935). This measure was apparently introduced by Partsch (1911), who termed it the reliefenergie, and was first used in the English language in 1935 in independent papers by Smith and by Huggins (1935).[1]

---

1 The former author is generally credited with introducing the concept of local relief into the English language literature, but Huggins apparently presented his paper at a professional meeting some months earlier.

These works, as well as many others (see Table 3.1), determined local relief for arbitrarily-bounded terrain samples such as squares, circles, or latitude-longitude quadrangles. In most cases, the size of the sample area was arbitrary, although Trewartha and Smith (1941, p. 31) stated that "the size of the rectangle for which relief readings are made appears to need adjustment for the degree of coarseness or fineness of the relief pattern." They did not indicate how the appropriate size could be determined. Wood and Snell (1960) used a variable sample area size -- they first determined the "grain" of the topography (see above, section 3.2.1), and then measured the relief for a circle with a radius equal to the grain. Wood and Snell (1957, 1959), Peltier (1962), and Evans (1972) compared the values of local relief determined over more than one size of area. Evans (1972, p. 30) pointed out that if the sample area "is so small (in relation to topographic wavelengths) that it is unlikely to contain a whole slope, 'relief' becomes simply a measure of gradient;" in order to make relief "as distinct and non-redundant a variable as possible" (p. 31), he recommended the use of "fairly large" sample areas. The areas should definitely be larger than the texture of the topography, and preferably larger than its grain. Data from Wood and Snell (1959, p. 9) support Evens' contention -- they found that the correlation between relief and slope declined as the size of the area over which they were measured increased. Salisbury (1962) studied the relationship between relief and slope for glacial deposits, and found the two to be closely related for older drift sheets, till plains, lake plains, and outwash, but poorly related on end moraines and sand dunes. This probably reflects the interaction of sample area size and texture.

In all of the above examples, local relief was determined for arbitrarily-bounded sample areas; local relief has also frequently been determined for drainage basins. The minimum elevation will be the basin mouth, while the

TABLE 3.1: SIZES OF ARBITRARILY-BOUNDED AREAS OVER WHICH LOCAL RELIEF WAS DETERMINED BY VARIOUS AUTHORS

authors	date	area (km^2)	type of area	# of sizes
Studies using one sample size:				
Chen	1947	1.00	square	
Harris	1969	1.00	square	
Hesler & Johnson	1972	2.59	square	
Swan	1967	3.34	square	
Abrahams	1972	7.52	square	
Huggins	1935	10.4	square	
Donahue	1972	10.4	square	
Batchelder	1950	15.0	quad.*	
Zakrzewska	1963	23.3	square	
King	1966	25.0	square	
Kaitanen	1969	25.0	square	
Hutchinson	1970	25.0	square	
Partsch	1911	32.0	-	
Trewartha & Smith	1941	34.0	quad.	
Smith	1935	65.5	quad.	
Hammond	1964	93.2	square	
Spreen	1947	203.	circle	
Ahnert	1970	400.	square	
More than one size used:				
Gassmann & Gutersohn	1947	0.25 to 28.0	square	13
Evans	1972	0.63 to 62.7	square	18
Wood & Snell	1957, 1959	0.81 to 414.	circle	8
Peltier	1962	2.59 & 259.	square	2
Wood & Snell	1960	18.3 to 399.	circle	7

* quad. = latitude-longitude quadrangle

maximum is usually, but not always, located on the basin perimeter. Maxwell (1960, p. 10-11) determined the "basin relief" as the "elevation difference between the basin mouth and upper end of the diameter", where basin diameter was determined trhough a complicated set of criteria, but was essentially "the longest dimension of the basin parallel to the principal drainage line". Since the size of drainage basins will vary, many workers have found it desirable to determine a dimensionless "relief ratio" or "relative relief number" by dividing the relief by some other linear dimension of the basin. The latter have included the basin diameter (defined above), basin perimeter (Melton, 1957) and square root of basin area (Melton, 1965).

3.3.2: Available Relief (H_a)

The concept of available relief was introduced by Glock (1932), and his definition was rephrased by Johnson (1933, p. 295) to read: "Available relief is the vertical distance from the former position of an upland surface down to the position of adjacent graded streams." Johnson pointed out that this could only be determined where the original upland surface could be identified from remnants and where there were "graded" streams. The latter involves the definition of the concept of "grade", which will not be discussed here. Local, available and drainage relief are illustrated diagrammatically in Figure 3.2. Glock stressed the importance of available relief in determining the land profile but, as Johnson noted, other factors such as drainage density and slope must also be considered.

In order to determine the average available relief, one would have to construct both the "original" and "streamline" surfaces (see Pannekoek, 1967, for a review of methods for constructing such surfaces), and to then divide the difference in the volumes under these surfaces by the area.

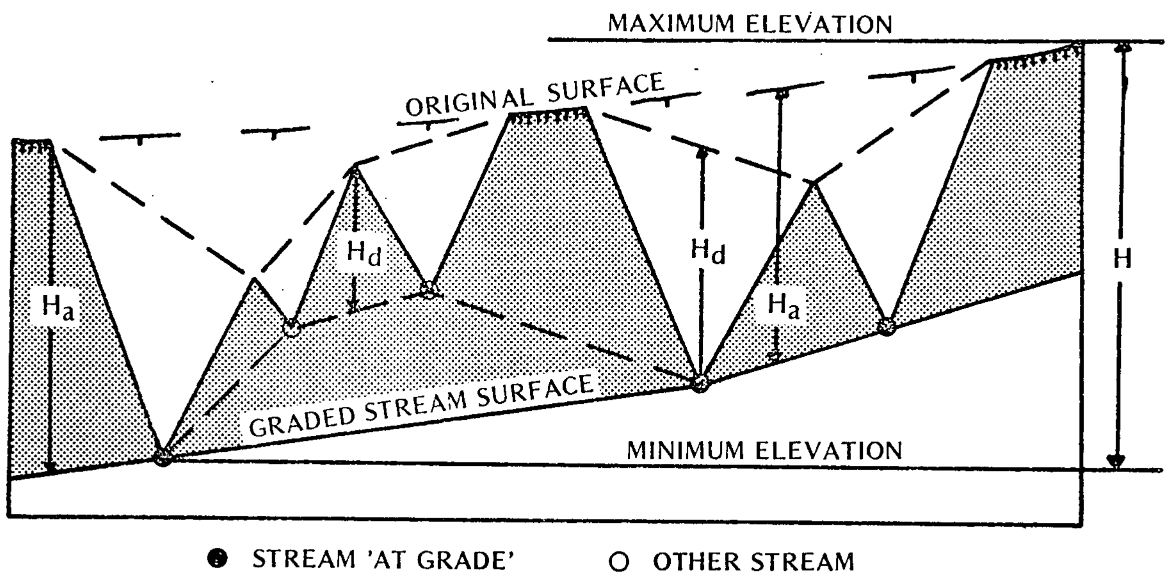


Figure 3.2: Hypothetical topographic profile illustrating various relief measures. H is the local relief for the entire profile, H_a Glock's available relief, and H_d the drainage relief. Dury's "available relief" would be the <u>mean</u> height of the shaded portion.

A different relief measure was discussed by Dury (1951), who unfortunately also used the term "available relief"; this was defined as "that part of the landscape which, standing higher than the floors of the main valleys, may be looked on as available for destruction by the agents of erosion working with reference to existing base-levels" (p. 339). He then defined the "mean available relief" as the average height of the land above the streamline surface, computed as the difference in volumes under the actual and streamline surfaces, divided by the area. This is clearly not the same as the available relief defined by Glock (1932) and Johnson (1933). Dury (1951, p. 342-3) also discussed the depth of dissection", which is identical to the Glock/Johnson concept of available relief.

3.3.3: Drainage Relief (H_d)

Glock (1932, p. 75) also defined a measure called the drainage relief as "the vertical distance through which rain water moves over the ground from the time the water first strikes the surface until it joins a definite stream." Johnson (1933, p. 301), however, pointed out that Glock later used the term to refer to the vertical distance between adjacent divides and streams, and proposed that this latter definition be adopted (see Figure 3.2). If in an area all the divides are at the elevation of the original upland surface and all the streams are "at grade", drainage relief will equal available relief; in contrast to the latter, however, drainage relief can always be determined. Strahler (1958, p. 295) stated that "local relief, H, is a measure of vertical distance from stream to adjacent divide" (i.e., local relief is equivalent to drainage relief), but this will only be true if the sample areas upon which local relief is based are large enough to include adjacent streams and divides and yet not so large that the slopes of the streams and divides themselves significantly increase the relief within the sample area. In Figure 3.2, the area over which H is determined is "large" and H exceeds H_d. Hormann (1971, p. 145) determined the mittlere Taltiefe ("mean valley depth") for drainage basins. First, a "roof" was constructed over the basin by linking points along the basin divide which were equidistant from the basin mouth by straight lines. The volume between this surface and the land surface wad divided by the basin area. This measure is "complementary" to Dury's "mean available relief".

3.3.4: Applications of Relief Measures

Relief has commonly been used in a descriptive way (e.g. Smith, 1935) or to delimit physiographic regions (e.g. Huggins, 1935), both alone and in conjunction with other variables. Some studies have, however, related relief to landscape processes, or to other aspects of physical geography. Schumm (1954, 1963) found that sediment yield was closely related to the ratio of basin relief to basin diameter for some small drainage basins in the southwestern United States. Schumm (1956) also related sediment yield to relief and slope for some smaller basins in the Perth Amboy badlands. Maner (1958) investigated the relationships between sediment yield and a number of basin characteristics, and found that the above relief ratio was the one most highly correlated with the dependent variable. Ahnert (1970) determined average basin relief as the mean of local relief values for 20 by 20 km squares spread over a number of drainage basins for which he had information concerning denudation rates. In the absence of stream incision, denudation will reduce relief; by using the empirical relationship between denudation rates and relief, Ahnert presented theoretical curves for relief reduction as a function of time, both with and without the effects of isostatic compensation. He later (1972) related these results to theoretical models for slope processes.

3.4: Slope

Evans (1972, p. 36) stated that "slope is perhaps the most important aspect of surface form, since surfaces are formed completely of slopes, and slope angles control the gravitational force available for geomorphic work." Mathematically, the tangent of the slope angle ($\tan\alpha$) is the first derivative of altitude, and it is as a tangent or per cent slope that this surface parameter is generally reported. Strahler (1956) also mapped slope sine, which is proportional to the downslope component of the acceleration of gravity. Strahler's (1950, 1956) work suggested that slope tangents had a normal distribution; Speight (1971), however, found that for a number of areas investigated, a log-normal distribution provided a better fit.

Unlike relief and most other geomorphometric parameters, which are only defined for finite subareas of a surface, slope is defined at every point as the slope of a plane tangent to the surface at that point. In practice, however, slope is generally measured over a finite distance, especially when data are obtained from a contour map. The size of area over which slope is measured will influence the values obtained, and the effect of recording intervals on slope values was discussed by Gerrard and Robinson (1971). Mean slope was generally much less sensitive to the recording interval than was maximum slope.

3.4.1: Average Slope: Line-Sampling Method

A method for estimating average slope proposed by Wentworth (1930) has been widely applied. The number (N) of intersections between a set of traverse lines and the contours in the sample area is counted, and the total length of the traverse lines (L) is measured. L divided by N is the mean horizontal distance between the contours, as measured along the traverse lines. This will tend to be larger than the mean orthogonal distance, and therefore a "correction factor" must be applied. If the traverse line intersects the contours at an angle θ, the true inter-contour distance will equal $\sin\theta$ times the traverse distance. If one assumes that all values of θ between 0 and 90 degrees are equally likely, then the true mean inter-contour distance should equal L/N times the mean value of $\sin\theta$, which is $2/\pi$, or 0.6366. The mean slope tangent estimate is then given by:

$$\tan\alpha = \frac{I\,(N/L)}{0.6366} \qquad (3.3)$$

where I is the contour interval in the same units as L. Wentworth presented the formula for use with L in miles and I in feet as:

$$\tan\alpha = \frac{I\,(N/L)}{3361} \qquad (3.4)$$

The method gives the mean slope for an area, but has been used to construct slope isopleth maps by assigning the slope for an area to a point at the area's centre (cf. Smith, 1939; Calef and Newcomb, 1953; Griffiths, 1964).

Other authors have used the number of contour intersections per length of traverse directly, without converting to an actual slope value. Wood and Snell (1957, 1960) used the "contour count" as a "measure of slope" (1957, p. 1), but in their 1959 paper converted this to slope using Wentworth's formula. Zakrzewska (1963) determined the "roughness" at a sample point as the number of contour intersections with the circumference of a circle centred at that point.

3.4.2: Average Slope: Other Methods

Raisz and Henry (1937) mapped average slope by determining areas of similar contour density (slope) subjectively. The mean slope (in feet per mile) was determined for each such area, and a choropleth map was produced. This approach has also been applied by some other writers (cf. Griffiths, 1964). Another method which has been widely used depends upon determining the slope at a sample of points distributed over the study area; these values may be averaged (cf. Strahler, 1956; Coulson and Gross, 1967) or "contoured" (cf. Strahler, 1956; Speight, 1968).

Ruhe (1950) and Rowan et al. (1971) determined slope for traverse segments between maxima and minima along the traverses. No attempt was made in either of these studies to correct for the angle between the traverse line and the contours.

In direct computer applications, a number of writers (Monmonier et al., 1966; Piper and Evans, 1967, cf. Evans, 1972; Park et al., 1970, 1971) have described methods for determining surface slope from digitized contour data. Sharpnack and Akin (1969), as well as Rase (1970, pers. oral comm.), computed both slope and aspect from an altitude matrix.

Griffiths (1964) compared the "subjective method" (essentially the Raisz and Henry approach), Wentworth method and "point sampling" method. He concluded that Wentworth's method was most accurate, and that the point sampling method produced "comparable" results with less effort.

3.4.3: Other Slope Parameters

Another slope parameter is the rate of change of slope, termed the "local convexity" by Evans (1972, p. 41). Mathematically, this is the second derivative of altitude, or the first derivative of slope. Convexity can be separated into downslope convexity and cross-slope convexity (contour curvature). Evans suggested that the problem of convexity could be "solved" by fitting quadratic surfaces to 3 by 3 sections of an altitude matrix. Convexity could then be determined by differentiating the resulting quadratic equation twice. Speight (1968, p. 243) examined both rate of change of slope (which he termed "slope gradient") and contour curvature. It is also possible to determine higher derivatives of altitude, but the possible physical meaning of such higher derivatives is obscure.

Closely related to mean slope is Strahler's ruggedness number, which was defined as HD_d by Strahler (1958, p. 289) as a result of dimensional analysis. In the case of a two-dimensional profile, the relationship among relief, drainage density, and slope can be easily shown. In Figure 3.3, H is the relief and b half the distance between channels, which equals half the inverse of D_d. One thus has the mean slope given by:

$$\tan \alpha = H/b = 2\,HD_d \tag{3.5}$$

or twice the ruggedness number. Strahler (p. 295) also introduced average slope into the ruggedness number, producing the geometry number:

$$\frac{HD_d}{\tan \alpha} \tag{3.6}$$

If H is a reasonable estimate of the drainage relief and if the two-dimensional case can be extended to three dimensions, this geometry number should equal 0.5 (see equation 3.5). The theoretical relationship is supported by the fact that Strahler found that while drainage density for his test basins ranged over two orders of magnitude, values of the geometry number remained between 0.4 and 1.0.

3.4.4: Application of Slope Measures

As in the case of relief (section 3.3.4), slope has been widely used in descriptive work, in physiographic classification, and in military work related to vehicle trafficability. Slope angle is a result of past or present geomorphic processes, and will also influence these processes (c f. Ahnert, 1972). Indeed, the analysis of slope profile form represents an important "sub-discipline of geomorphology (for example, Institute of British Geographers, 1971; Carson and Kirkby, 1972; Young, 1972).

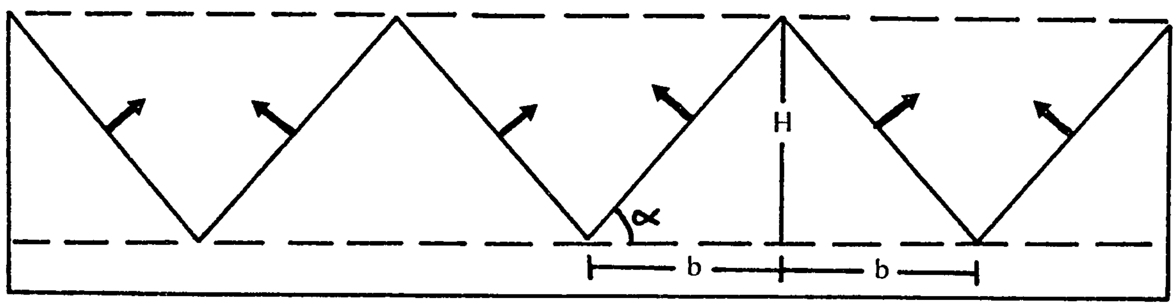


Figure 3.3: Diagrammatic topographic profile illustrating the relationships among relief, slope, and roughness (see equations 3.5, 3.10, and 3.11).

3.5: Dispersion of Slope Magnitude and Orientation

In addition to slope steepness, slope aspect or direction may be considered, either separately or together with slope angle. Evans (1972, p. 41) proposed that the combined analysis of slope magnitude and orientation would produce "undesirable hybrid results; it is better to separate variability in gradient from variability in aspect." If this is done, the aspect data should be analyzed using two-dimensional vector analysis (cf. Curray, 1956). While such separation may be desirable in some cases, the distribution of orthogonals to the land surface (which summarize both types of information) is essentially three-dimensional, and its analysis as such would seem to be appropriate.

Chapman (1952) presented a potentially useful method for examining slope steepness and aspect. Both the aspect (orientation) and slope (dip) of the land surface were determined for a sample of points on a regular grid. The points were then plotted on a Schmidt net and contoured in the same way as other orientation data in the earth sciences are often presented. Chapman suggested that these diagrams would probably be useful in relating slopes to structure or the effects of glacier movement, and Newell (1970) successfully used the technique in this context. One of the computer programs presented by Hobson (1967, 1972) represents a logical extension of this work, treating the perpendiculars to slope units as vectors and applying well-established mathematical approaches to the analysis of three-dimensional orientation data (cf. Fisher, 1953; Steinmetz, 1962). Unit vectors orthogonal to triangular facets formed by inserting diagonals into a regular grid were summed and the length of the vector sum (R) was determined. Hobson then calculated k (which is the estimate of the precision parameter κ for the spherical normal distribution of Fisher, 1954) as:

$$k = (N-1) / (N-R) \qquad (3.7)$$

As a surface approaches planarity, the vectors will become parallel, R will approach N (the number of vectors), and k will become very large. Intuitively, a plane should have a roughness of zero, and thus the inverse of k would represent a more "reasonable" roughness measure. Since Hobson's method was based on a regular grid, all triangles have the same horizontal area and similar true areas, and hence the use of unit vectors is not unreasonable. If based upon irregularly-distributed surface specific points, however, there may be a considerable variation in triangle size. It would seem appropriate to weight the vector orthogonal to each triangle by the triangle's true area. If this is done, however, k and its inverse cannot be determined through equation 3.7. Some manipulation of that equation gives:

$$\frac{1}{k} = \left[\frac{N}{N-1}\right] \left[1 - \frac{R}{N}\right] \cong \left[\frac{100 - L(\%)}{100}\right] \text{(for large N)} \qquad (3.8)$$

where L(%) is 100 (R/N), the vector strength in per cent. For weighted vectorial analysis, L is defined as 100 times the weighted vector sum divided by the sum of the weights. It is herein proposed that the best measure of "vector dispersion" roughness is the <u>roughness factor</u> $\mathbb{R}$, defined by:

$$\mathbb{R} = 100 - L(\%) \qquad (3.9)$$

In the case of unit vectors and large N, $\mathbb{R}$ will approximately equal 100 times the inverse of k.

As in the case of slope, the roughness factor can be related to relief and ridge spacing through reference to Figure 3.3. For $\mathbb{R}$, the vertical component of each orthogonal vector will equal $\cos \alpha$, while the horizontal components will cancel out, leaving:

$$\mathbb{R} = 100 \, (1 - \cos \alpha) \qquad (3.10)$$

Substituting the value for cos α gives:

$$\mathbb{R} = 100\left(1 - \frac{b}{\sqrt{H^2 + b^2}}\right) \qquad (3.11)$$

Turner and Miles (1967) applied Hobson's (1967) vector program to twenty-five sample areas; twelve of these were derived from Stone and Dugundji's (1965) microterrain maps and provide a basis for examining the relationships among the parameters used by these authors, including $\mathbb{R}$ and H. The other thirteen samples were based on macroterrain from 1:24,000 scale maps. In addition to k, Turner and Miles determined the local relief (H), and a variability factor v, the local relief divided by the logarithm of k; the writer estimated $\mathbb{R}$ as the inverse of k. Linear correlation coefficients were determined among ten roughness measures for the twelve common terrain samples. In addition, correlations were determined separately among Stone and Dugundji's six variables(16 cases) and among the four derived from Turner and Miles (25 cases). The only statistically significant correlations based on the common terrain samples which did not reflect functional relationships were those between mean and maximum amplitude, and between H and $\mathbb{R}$. The latter pair of variables were not significantly correlated over the twenty-five Turner and Miles samples. This is almost certainly due to the difference in scale between the 1:24,000 and microterrain maps (1 to 2 orders of magnitude). In Figure 3.4, $\mathbb{R}$ (as estimated as the inverse of k) is plotted against H for these 25 samples and for six others analyzed in Chapter 6. Curves of the form given in equation 3.11 for various values of b have been plotted in Figure 3.4. These have been fitted "by eye" to the groups of points for each of the six scales represented. It appears that each scale has a reasonably consistent "characteristic wavelength" which influences the relationship between H and $\mathbb{R}$.

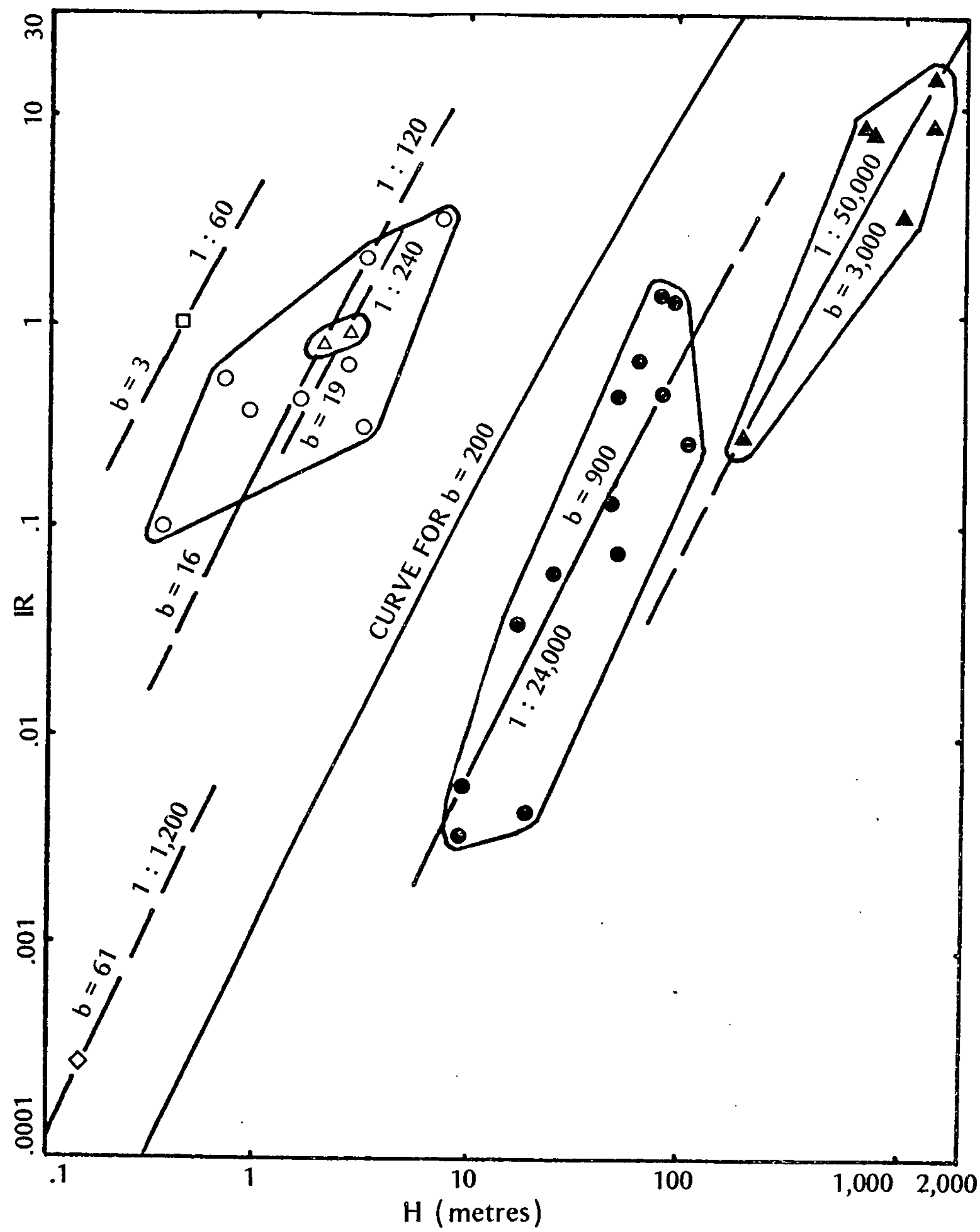


Figure 3.4: Relationship between local relief and roughness factor. Open symbols represent micro-terrain from Turner and Miles (1967). Solid symbols are macro-terrain (circles from Turner and Miles; triangles from this study). Curves are based on equation 3.11.

In a related line of research, Hayre and Moore (1961) determined theoretical scattering coefficients for terrain, based on autocorrelation functions determined from contour map data. Hayre (1962) then used observed radar return rates to estimate the roughness of the lunar surface.

3.6: Hypsometry

Clarke (1966, p. 237) defined hypsometry as "the measurement of the interrelationships of area and altitude." Evans (1972, p. 42-48) reviewed this concept under the heading: "Regional convexity (dissection, aeration)." Most of these measures, which describe aspects of the distribution of landmass with elevation, are based upon the hypsometric curve.

3.6.1: The Hypsometric Curve and its Variations

Monkhouse and Wilkinson (1952, p. 112-115) noted that there are three common sorts of graphs used to report hypsometric data. These are:

(a) the area-height curve;

(b) the hypsometric (or hypsographic) curve, sometimes called the absolute hypsometric curve;

(c) the percentage hypsometric curve.

The first of these methods, the area-height curve, plots the area in a band at a particular elevation against elevation, and by convention, elevation is plotted on the y-axis. If relative area is used, the diagram is a plot of the probability density function for the heights in the area. The relative frequencies of elevations are generally more easily seen on this type of curve than on the hypsometric curves.

The absolute hypsometric curve is a graph of the absolute or relative area above a certain elevation plotted against that elevation, and is essentially a cumulative frequency for the elevations. Once again, elevation is conventionally plotted on the y-axis and area (representing frequency) on the x-axis.

Clarke (1966, p. 241) pointed out that this curve does not represent an "average profile", since it does not record the slope between contours. Nevertheless, a section of the curve with a low slope indicates a larger amount of the surface at or near a particular elevation; this would generally indicate gentler slopes near that elevation. Absolute hypsometric curves have been determined for the earth's surface as a whole, countries, natural regions, islands, and drainage basins. While usually plotted on simple arithmetic graph paper, various special sacles have also been employed. Tanner (1962), for example, plotted the percentage of the earth's surface area lying above certain elevations on log-probability paper, and was able to separate the curve into four Gaussian components. Chorley (1958) found that the hypsometric curve for a drainage basin he examined plotted as a straight line on arithmetic-probability paper.

The third and most widely used form of curve is the relative or percentage hypsometric curve, often termed simply the hypsometric curve.[1] It plots relative area above a height against relative height, and is the graph of the hypsometric function, here termed a (h), where h (the relative height) is defined by:

$$h = \frac{z - z_{min}}{z_{max} - z_{min}} \qquad (3.12)$$

where z is the actual elevation, and z_{max} and z_{min} are the highest and lowest elevations, respectively, within the study area. As in the previous cases, h is conventionally plotted on the y-axis. It is this form of the hypsometric curve and function upon which some important terrain parameters are based.

1 This form of the hypsometric curve is often attributed to Strahler (1952) (for example, see Chorley and Morley, 1959, p. 566); relative hypsometric curves were presented earlier by Imamura (1937, cf. Evans, 1972, p.42), Gassmann and Gutersohn (1947), and Langbein and others (1947), only the latter being cited by Strahler.

3.6.2: The Hypsometric Integral (HI)

The most widely used parameter based on the hypsometric curve is the hypsometric integral, here designated HI. This parameter, as defined by Strahler (1952, p. 1121), is given by:

$$HI = \int_0^1 a(h)\, dh \qquad (3.13)$$

Strahler pointed out that geometrically, this value is equal to the ratio of the volume between the land surface and a plane passing through the minimum elevation to the volume of a "reference solid" bounded by the perimeter of the area and planes passing through the minimum and maximum points. Graphically, HI can be determined by measuring the area under the relative hypsometric curve. Strahler (p. 1130) proposed that the value of the hypsometric integral reflects the "stage" of landscape development. Those areas having HI values above 0.6 were considered to be in a "youthful" or equilibrium phase, while drainage basins in equilibrium should have hypsometric integrals between 0.6 and 0.35. Values below 0.35 were thought to characterize a transitory "monadnock phase" in landscape development.

Pike and Wilson (1971) proved that the elevation-relief ratio (E) of Wood and Snell (1960) is mathematically equal to the hypsometric integral. The former is defined by:

$$E = \frac{\bar{z} - z_{min}}{z_{max} - z_{min}} \qquad (3.14)$$

where $\bar{z}$ is the mean elevation. From equations 3.12 and 3.14, it can be seen that E is just the mean relative height ($\bar{h}$). Evans (1972, p. 42) pointed out that this same parameter was used much earlier by Peguy (1942, p. 462), and termed the "coefficient of relative massiveness" by Merlin (1965). While Strahler's (1952) method for determining the hypsometric integral involves much laborious use of a planimeter to determine inter-contour areas, the elevation-relief ratio can be determined much more quickly, with the mean elevation being determined from a sample of points. Pike and Wilson (1971, p. 1081) stated that "experience has shown that a sample of 40 to 50 elevations will ensure accuracy of E to, on the average, 0.01, the value to which area-altitude parameters customarily are read." It is important that the maximum and minimum elevations are determined from an inspection of the entire sample area; gross errors in E can result if the highest and lowest grid values are used (see section 5.4). Evans (1972, p. 58), however, used only grid values to estimate the hypsometric integral for sub-matrices ranging from 3 by 3 (9 points) to 47 by 47 (2209 points). For the smaller sub-matrices at least, Evans' estimates of H are probably in serious error.

Other methods for approximating the hypsometric integral or curve have been proposed. Haan and Johnson (1966) suggested that the elevations of a sample of randomly-located points could be used to construct hypsometric curves, with a considerable saving in time. Chorley and Morley (1959) proposed that the hypsometric integral could be estimated by approximating the drainage basin by a simple geometric form, "the intersection of a lemiscate cylinder with an inverted cone, centered at the lemniscate origin" (p. 556). The accuracy of this method depends upon the degree to which the geometrical form actually approximates the basin, particularly the fit of the lemniscate loop to the basin perimeter (Chorley _et al._, 1957). Chorley and Morley found that the method produced a systematic error, and proposed a correction factor. Turner and Miles (1967) used a computer program to interpolate a dense regular grid from a sample of points; numbers of grid points falling within altitudinal bands were used in producing hypsometric curves. They found that their method produced results closer to planimetered values than did the corrected

Chorley and Morley approach. It would seem that the elevation-relief ratio represents a more accurate and more easily applied approximation to the hypsometric integral than do the above. Furthermore, the elevation-relief ratio can be determined for arbitrarily-bounded areas (Wood and Snell, 1960; Pike and Wilson, 1971), while the Chorley and Morley method can only be used for drainage.

3.6.3: Other Parameters Related to the Hypsometric Curve

A number of parameters besides the hypsometric integral have been derived from the hypsometric curve. Strahler (1952, p. 1130) noted that most hypsometric curves show a characteristic "s-shape", and proposed a parameter to indicate the sinuosity of the curve. Low values of this parameter indicated very sinuous curves. Evans (1972, p. 47-48) found a strong correlation between the hypsometric integral and the skewness of the distribution of elevations in cases having the same sinuosity. For any constant value of HI, higher skewness was associated with lower values of Strahler's sinuosity parameter. Tanner (1959, 1960) suggested that the skewness and kurtosis of the height distribution function (essentially the hypsometric function) could be used to "characterize various geomorphic regions" (1960, p. 1525). Examination of Tanner's diagrams seems to confirm Evans' result that skewness is closely related to the hypsometric integral, and also suggests that Strahler's sinuosity parameter is closely related to kurtosis. Sinuosity, as measured by Strahler's parameter or the kurtosis, has not (to the writer's knowledge) been investigated in detail or related to other geomorphometric measures.

Gassman and Gutersohn (1947) determined a parameter called the kotenstreuung. For computation, this has been shown to equal the standard deviation of the elevations, and was derived from the absolute hypsometric function. They also determined the relieffactor, which equals twice the kotenstreuung divided by the local relief. This is twice the standard deviation of the relative hypsometric function. Gassman and Gutersohn also determined the mean elevation by using the hypsometric integral, "reversing" the use of the elevation-relief ratio proposed above; this method of determining the mean elevation was employed earlier by Martonne (1941).

3.6.4: Other Parameters Related to Hypsometry

In addition to those related to the hypsometric curve, other parameters have been proposed to characterize the relationship between area and altitude, sometimes also including slope. None of these have been as widely used as the hypsometric integral; since many of these have been reviewed by Clarke (1966, p. 243-248) and by Evans (1972, p. 44-45), most will not be reviewed herein. Hammond (1964, p. 15) combined slope and height in an area-elevation measure. His general profile character index was defined as the percentage of gentle slopes (tan α less than 0.08) lying above or below the mean elevation. Pike and Wilson (1971, p. 1079-80) noted that this index measures a similar aspect of terrain form to the hypsometric integral. This measure may be undefined in some areas if there are no slopes gentler than the critical value.

3.6.5: Application of Hypsometric Measures

All or most of the parameters discussed above have been used in a simply descriptive sense or in physiographic classification. Only the hypsometric integral, however, has been related to geomorphic processes. In most cases, HI has been determined for drainage basins. Strahler (1957, p. 918-920) listed a number of works between 1952 and 1956 which used this parameter; none of these studies found any relationship between HI and various hydrologic or sediment yield measures. Chorley (1957, p. 630) measured hypsometric integrals for 27 drainage basins, but did not use this parameter in subsequent analyses nor comment on its omission. Eyles (1969) studied stream long profile form, basin relief, and basin hypsometric integral for 410 fourth-order drainage basins in Malaysia. He graphed the hypsometric integral against relief and presented an "approximate curve of best fit drawn 'by eye' "(p. 29). If one assumes that relief is continuously reduced with time (cf. Ahnert, 1970) and that space can be substituted for time, Eyles' line suggests a period of equilibrium, a monadnock phase, and an eventual return to equilibrium. An initial inequilibrium phase does not appear to be represented in these data.

3.7: Review and Parameters to Be Investigated

In review, the most fundamental concepts of geomorphometry are the basic horizontal and vertical scales of the topography. Horizontal variations are encompassed by the concepts of grain (largest significant wavelength) and texture (shortest significant wavelength); grain will not be investigated explicitly, but three measures of texture, namely drainage density (D_d), source density (D_s), and peak density (D_p) will be considered in the next chapter.

Vertical scale is generally termed "relief"; this terrain concept will be represented in further analyses by the local relief (H), the most widely employed relief measure. The relationships between horizontal and vertical scale will be examined through the mean slope ($\tan \alpha$), while the three-dimensional interaction of slope steepness and aspect will be studied through the roughness factor ($\mathbb{R}$).

Relatively independent from horizontal and vertical scales is the distribution of mass within the vertical range of the topography. This concept will be investigated through the hypsometric integral ($\mathbb{H}$).

While there may be some redundancy among the parameters noted above, it is believed by the writer that with the possible exception of grain, all important terrain information is contained within these parameters. In the next chapter, the relationships among the measures will be studied.

Chapter 4: Terrain Variability in Southern British Columbia, and Relationships among Variables

Before beginning the comparison of the computer terrain storage systems, a "pilot study" was conducted. The principal objectives of this were threefold:

(1) to provide information about terrain variability in southern British Columbia, and thus guide in the selection of terrain samples for more detailed analysis;

(2) to investigate the relationships among the parameters selected in the preceding chapter; and

(3) to provide empirical data for the evaluation of some of the theoretical errors in estimating parameters, which will be discussed in the next chapter.

Values for a number of geomorphometric parameters were determined for square terrain samples using simple techniques not including computer analysis. The roughness factor ($\mathbb{R}$) could therefore not be examined, but the other important parameters listed at the end of the preceding chapter were all studied.

4.1: Selection of Sample Areas

In order to obtain a relatively unbiased sample of the terrain of southern British Columbia, a stratified random sampling design was employed. From each of the forty-two 1:250,000 scale map sheets which cover British Columbia south of 54 degrees latitude, one of the thirty-two 1:50,000 scale maps making up that sheet was selected with the aid of a table of random numbers. Because coverage of the area at the larger scale is incomplete, some of the randomly-selected maps were not available. In such cases, and in instances where the selected map fell <u>entirely</u> outside British Columbia, another map was picked. From each map, one 7 by 7 kilometre square of terrain was examined. If the Universal Transverse Mercator grid was printed on the map, the sample was generally centred at the intersection of the two major ("10th kilometre") grid lines closest to the centre of the map; this would facilitate later location of the sample areas on the 1:250,000 s ale maps, if desired. Where the grid did not appear, the sample square was usually placed over the centre of the map. Samples were relocated if more than one third of the area contained water surfaces. The locations of the forty-two samples, together with the major physiographic subdivisions of the study area, are shown in Figure 4.1; two of the samples (4, 9) fell in Alberta, although the maps from which they were drawn were in part in British Columbia.

Since it was not possible to adheré strictly to the original random sample, tests were made of the randomness of the terrain samples actually used. As noted above, each 1:250,000 scale map contains thirty-two 1:50,000 scale half-sheets (see Figure 4.2). The numbers of these thirty-two "cells" containing exactly zero, one, two, et cetera, samples were determined and compared to the frequencies predicted according to the Poisson distribution. A chi-square test indicated that the two sets of frequencies were not significantly different at the 95 per cent level.

Of twenty major physiographic divisions of British Columbia given by Holland (1964), ten occur at least in part south of 54 degrees latitude. These, together with the sample numbers and respective map-areas falling within each division, are listed in Table 4.1. The actual distribution of the forty-two terrain samples among these ten regions was compared with an even distribution based on the areas of the subdivisions, once again using the chi-square test (see Table 4.2). The distributions were not significantly different at the 95 per cent level. The larger than expected number of samples in the first three subdivisions is probably at least in part due to the coastal locations of these regions (see Figure 4.1). Since samples falling on the ocean were not accepted,

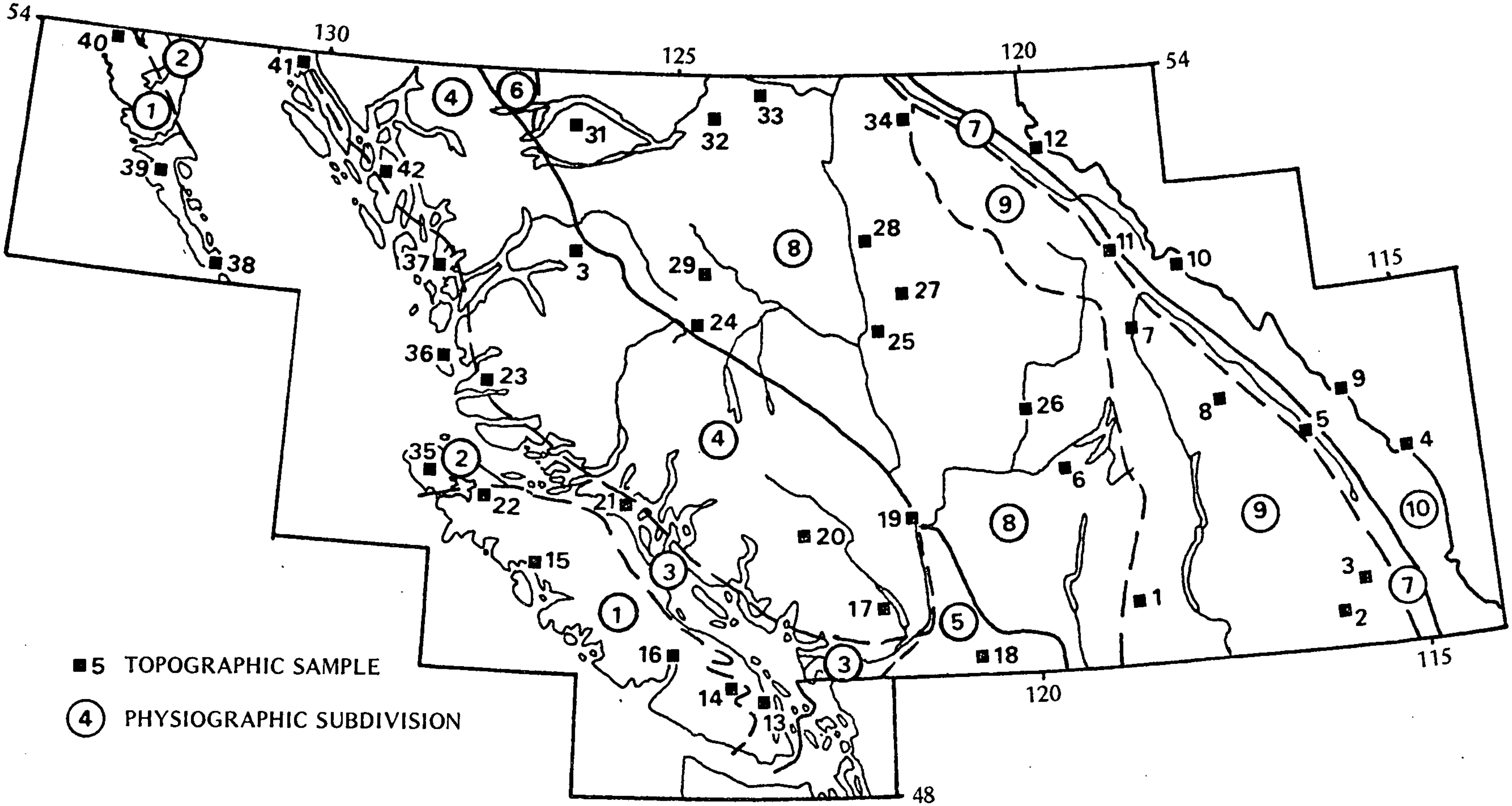


Figure 4.1: Physiographic subdivisions of southern British Columbia (see Table 4.1) with locations of stratified random sample of terrain analyzed in Chapter 4.

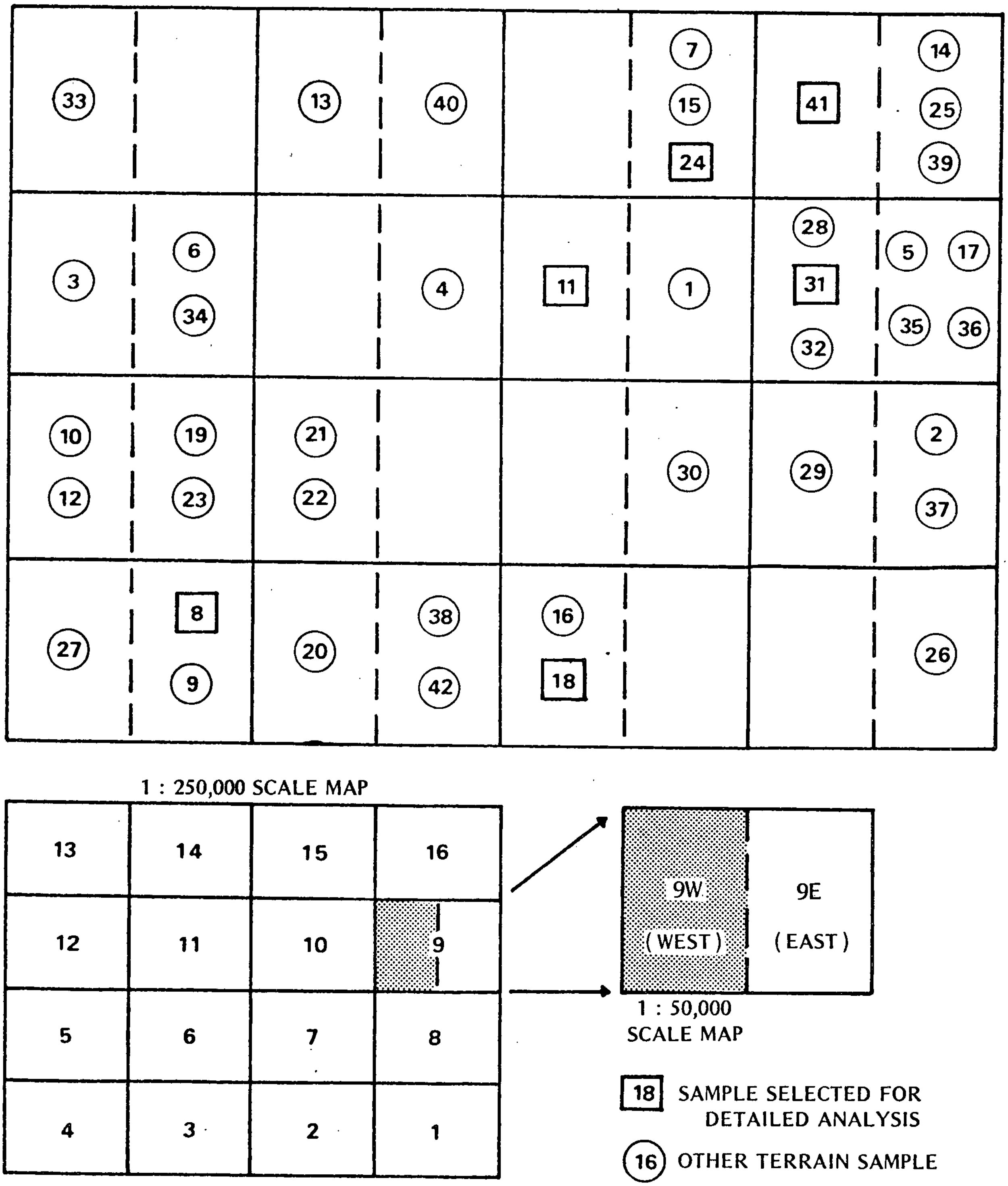


Figure 4.2: Distribution of terrain samples among the 32 1:50,000 scale sheets which make up a 1:250,000 scale map sheet. See text for discussion.

TABLE 4.1: PHYSIOGRAPHIC SUBDIVISIONS OF SOUTHERN BRITISH COLUMBIA, AFTER HOLLAND (1964), WITH SAMPLE NUMBERS AND MAP-AREAS FOR TERRAIN SAMPLES ANALYZED IN CHAPTER FOUR

Western System			
Outer Mountain Area			
Insular Mountains (1)			
	14: 92C/16E	22: 92L/6W	39: 103C/16E
	15: 92E/15E	38: 103B/3E	40: 103F/14E
	16: 92F/2W		
Coastal Trough			
Hecate Depression (2)			
	35: 102I/9E	37: 103A/8E	*41: 103G/16W
	36: 102P/9E		
Georgia Depression (3)			
	13: 92B/14W	21: 92K/6W	
Coastal Mountain Area			
Coast Mountains (4)			
	17: 92G/9E	20: 92J/3W	30: 93D/7E
	19: 92I/5E	23: 92M/5E	42: 103H/3E
Cascade Mountains (5)			
	*18: 92H/2W		
Interior System			
Central Plateau and Mountain Area			
Hazelton Mountains (6)			
	(no samples)		
Rocky Mountain Trench (7)			
	5: 82K/9E	*11: 83D/10W	
Southern Plateau and Mountain Area			
Interior Plateau (8)			
	6: 82L/12E	27: 93A/4W	32: 93F/9W
	*24: 92N/15E	28: 93B/9W	33: 93G/13W
	25: 92O/16E	29: 93C/8W	34: 93H/12E
	26: 92P/1E	*31: 93E/9W	
Columbia Mountains (9)			
	1: 82E/10W	3: 82G/12W	*8: 82N/4E
	2: 82F/8E	7: 82M/15E	
Eastern System			
Rocky Mountain Area			
Rocky Mountains (10)			
	4: 82J/11E	10: 83C/5W	12: 83E/5W
	9: 82O/4E		

* indicates sample selected for more detailed analysis

TABLE 4.2: COMPARISON OF DISTRIBUTION OF 42 TERRAIN SAMPLES AMONG TEN PHYSIOGRAPHIC DIVISIONS WITH EXPECTED DISTRIBUTION BASED ON DIVISION AREAS

physiographic division		per cent of area	expected (e)	observed (o)	$\frac{(e-o)^2}{e}$
1.	Insular Mountains	7.6	3	7	5.33
2.	Hecate Depression	4.8	2	4	2.00
3.	Georgia Depression	3.2	1	2	1.00
4.	Coast Mountains	24.6	10	6	1.60
5.	Cascade Mountains	1.5	1	1	0.00
6.	Hazelton Mountains	0.5	0	0	----
7.	Rocky Mountain Trench	1.6	1	2	1.00
8.	Interior Plateau	33.8	14	11	0.64
9.	Columbia Mountains	15.8	7	5	0.57
10.	Rocky Mountains	6.6	3	4	0.33
	Sums	100.0	42	42	$\chi^2 = 12.47$*

* not significant at the 95 per cent level

samples would tend to be "concentrated" in the land areas of map sheets containing considerable water.

4.2: Data Collection

As stated above, each terrain sample consisted of a 7 by 7 kilometre square; the selection of this sample area size was arbitrary. Within each area, a 7 by 7 grid with a one kilometre spacing was used in determining some terrain measures. At each of the forty-nine grid intersections, the elevation was determined, and the type of surface at the point (e.g. land, ocean, lake, or glacier or snowfield) was also noted. The number of intersections between the grid lines and contours, and also between the grid lines and the "blue line" stream network were counted. The elevations of the highest and lowest points within the area, the number of closed hilltop contours, the total length of streams, and the number of stream sources were also determined for each sample area.

4.3: Data Analysis

4.3.1: Drainage Density (D_d)

Drainage density was estimated for each sample area by measuring the total length of blue stream lines on the map, in kilometres, and dividing by the area. The number of intersections between the grid lines and the drainage net (N) was counted and divided by the total length of traverse (L). Carlston and Langbein (Unpub., 1960; cf. McCoy, 1971) developed a theoretical equation which proposed that the drainage density should be approximated by:

$$D_d = 1.57\ N/L \qquad (4.1)$$

The empirical evidence collected here appears to support this equation.

When a histogram of drainage density was prepared (Figure 4.3 a), the observations tended to cluster around 0.6 km^{-1}, but with a number of "outliers" having values above one. The writer had observed during the data collection

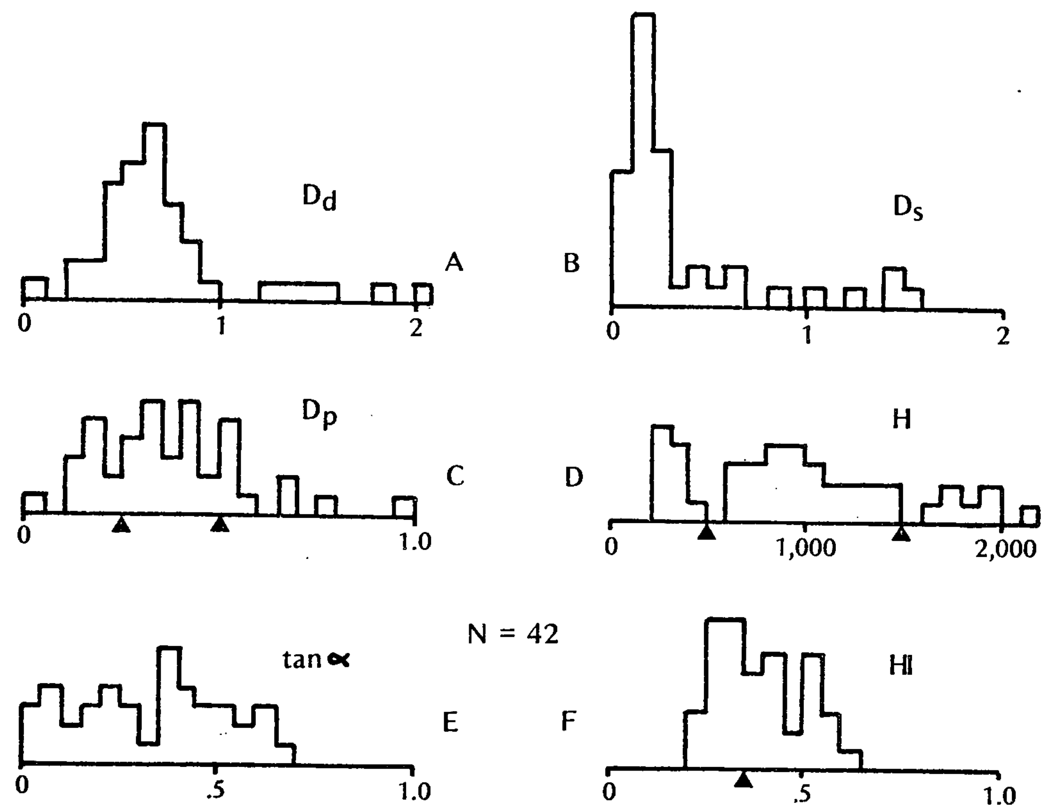


Figure 4.3: Histograms for six geomorphometric parameters. Triangles indicate the break points for three of the parameters.

that some of the older maps appeared to have higher drainage densities than newer ones. A statistically significant inverse correlation was found between D_d and the year of map publication. Drainage density was also significantly correlated with mean annual precipitation at the sites, and it was thought that this might explain the correlation between map age and drainage density, since most of the older maps were coastal. The correlation between map date and precipitation was not statistically significant, however, suggesting that the variation in the drainage net is at least in part cartographic (see section 1.1). Because of this problem, and because there were no well marked breaks in the distribution, drainage density was not used to divide the samples into groups having similar terrain.

4.3.2: Source Density (D_s) and Peak Density (D_p)

The numbers of stream sources and of closed hilltop contours (peaks) were determined and divided by the land area of the sample areas. Source density was found to be closely related to drainage density ($r^2 = 0.847$), but would also be dependent upon the drainage net depicted on the map, and so was not used in further analysis. A histogram for this parameter is shown in Figure 4.3b.

The histogram for peak density (Figure 4.3c) showed poorly developed breaks at about 0.25 and 0.50 km^{-2}; these were used to classify the terrain samples.

4.3.3: Local Relief (H)

The maximum and minimum elevations within each sample area, as determined by a visual inspection of the contours, were used to determine the local relief. This should be within one contour interval of the actual value and, if the maps are accurate, must be within two contour intervals. The maximum and minimum of the 49 grid heights were also determined; the difference between these was designated H*, the grid estimate of the local relief. Theoretical aspects of the relationship between the true and grid values of local relief will be discussed in section 5.1.

Histograms of local relief were drawn for each of seven physiographic divisions, and for the combined samples (see Figure 4.3d). The latter contained two "breaks" which were used to divide the data into three relief classes: "low" relief, less than 500 metres (10 samples); "moderate" relief, 500 to 1,500 metres (25 samples); "high" relief, more than 1,500 metres (7 samples).

4.3.4: Mean Slope (tan α)

The mean slope for each area was estimated using the Wentworth method (section 3.4.1). The total length of traverse was 98 kilometres, except where lakes or ocean reduced the land area; in these cases, the length of traverse was reduced by 2 km for each grid intersection falling on a water surface.

The histogram for average slope (Figure 4.3e) shows a rather poorly defined break at about 0.3. The high correlation between mean slope and relief for the samples ($r^2 = 0.679$) clearly indicates that these measures are not independent, and thus mean slope was not used in classifying the sample areas.

4.3.5: Hypsometric Integral (HI)

The value of the hypsometric integral for each sample was estimated using Wood and Snell's (1960) elevation-relief ratio. The mean of the elevations of those grid points which did not fall on lakes or the sea was used as an estimate of the mean height of the terrain. The formula for the elevation-relief ratio (equation 3.14) involves both the minimum elevation and the local relief; here, the hypsometric integral was computed twice: HI was based on the "true" minimum and maximum elevations, while H* was based on the grid estimates of these values. Theoretical errors in HI* will be discussed in section 5.4.

Histograms for this parameter were prepared (see Figure 4.3f), but in this case there were no clear breaks in the distribution. When Strahler's (1952) divisions at 0.35 and 0.60 were applied, it was found that only one sample had a hypsometric integral above 0.60 (sample 1:0.602). Thus essentially none of the areas examined were in the "youthful" or "inequilibrium" stage. Nineteen of the forty-two samples had HI values below 0.35 and would fall into Strahler's "monadnock phase", the remainder being essentially in equilibrium. While the hypsometric integral for an arbitrarily-bounded terrain sample is not necessarily the same as those of its constituent drainage basins (see section 5.4), the value of 0.35 was nonetheless used to divide the samples into low or intermediate HI values.

4.3.6: Relationships among Variables

In order to better understand the relationships among terrain and related parameters (see Table 4.3), linear correlation coefficients among the twelve variables listed in Table 4.3 were computed. Table 4.4 indicates all correlation coefficients which were statistically-significant at the 95 per cent level. The correlations were then examined using the same approach as Melton (1958); Figure 4.4 illustrates the three isolated correlation sets which form the cores of three variable systems, namely "drainage", "hypsometry", and "relief". Peak density (D_p) was not significantly correlated with any other variable. Factor analysis was also applied to the data, and produced essentially the same result .

TABLE 4.3: VARIABLES INCLUDED IN CORRELATION ANALYSIS

variable number	symbol	name
1	D_d	Drainage density
2	N/L	Drainage net intersections
3	D_s	Source density
4	D_p	Peak density
5	H	Local relief
6	H*	Grid estimate of local relief
7	$\tan \alpha$	Average slope tangent
8	HI	Hypsometric integral
9	HI*	Grid estimate of HI
10	$\bar{z}$	Mean elevation
11	p	Mean annual precipitation
12	t	Year of map publication

TABLE 4.4: STATISTICALLY SIGNIFICANT (95 PER CENT LEVEL) LINEAR CORRELATION COEFFICIENTS AMONG THE VARIABLES IN TABLE 4.3

D_d	N/L	D_s	D_p	H	H*	tan α	HI	HI*	$\bar{z}$	p	t	
-	0.990	0.921								0.473	-.496	D_d
	-	0.927								0.468	-.485	N/L
		-								0.554	-.479	D_s
			-									D_p
				-	0.987	0.824			0.419			H
					-	0.797			0.364			H*
						-		0.323		0.602		tan α
							-	0.887	0.364			HI
								-				HI*
									-	-.445	0.336	$\bar{z}$
										-		p
											-	t

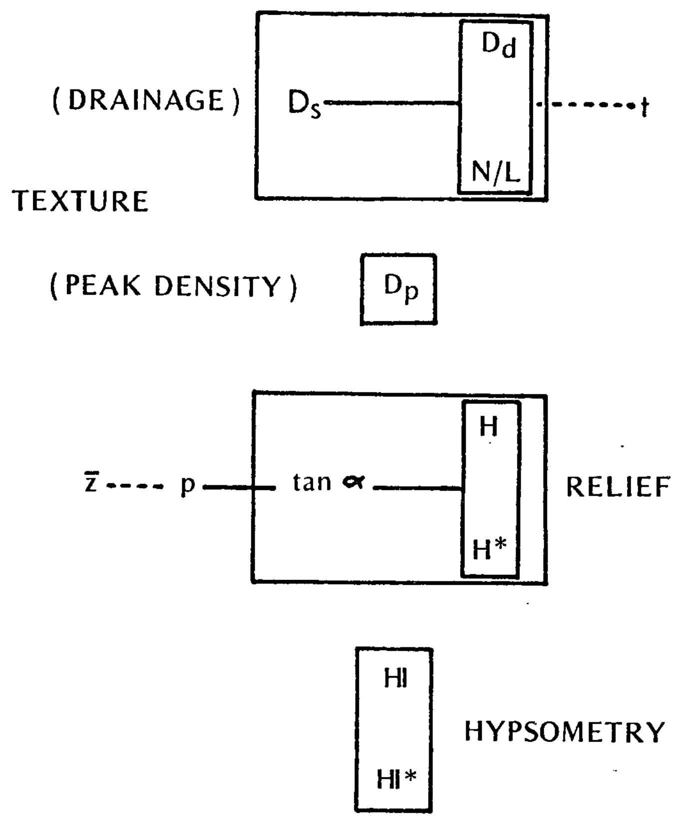


Figure 4.4: Correlation structure among twelve terrain and related parameters (constructed in the manner proposed by Melton, 1958). The outer boxes enclose isolated correlation sets; dotted lines indicate inverse correlations.

4.4: Classification of Samples and Selection of Areas for Further Analysis

Three independent terrain variables, namely relief, hypsometry, and peak density, were used to divide the forty-two samples into groups having similar terrain. The independence of the parameters is indicated by the fact that the maximum r^2 value among the three pairs was 0.063. The break points in the distributions of the variables were given above. As there were three classes each for relief and peak density and two for the hypsometric integral, there are eighteen possible groups -- of these, fifteen contained at least one sample (see Table 4.5). An attempt was made to select six samples for further analysis (in Chapter 6) from among the classes in approximately the same ratios as the total numbers of samples; a table of random numbers was used to aid in the final selections. The exact values of a number of selected geomorphometric parameters for the selected areas are shown in Table 4.6, while values for all forty-two areas analyzed in this chapter are given in Appendix II.

Using a polar planimeter to determine inter-contour areas, hypsometric curves were constructed for each of the six selected areas (Figure 4.5); curves based on the 49-point samples of elevations (cf. Haan and Johnston, 1966) were similar to those shown. The values used to construct the hypsometric curve were also used to calculate the hypsometric integral -- these values will be used as the "standard" to which estimates of H will be compared in subsequent sections.

4.5: Description of Areas Selected for Further Analysis[1]

4.5.1: Sample 8: Illecillewaet Map-area (82N/4E)

The terrain sample from the Illecillewaet map-area is located in the northern part of the Selkirk Mountains subdivision of the Columbia Mountains. The minimum elevation of 2880 feet (878 m) occurs in the valley of the Incomappleux River, while the maximum (9050 feet; 2758 m) is an unnamed

---

1 Physiography after Holland, 1964

TABLE 4.5: CLASSIFICATION OF 42 TERRAIN SAMPLES USING LOCAL RELIEF (H), HYPSOMETRIC INTEGRAL (HI), AND PEAK DENSITY (D_p). NUMBERS OF OBSERVATIONS IN CLASSES ARE IN PARENTHESES; SAMPLES FOR FURTHER ANALYSIS ARE UNDERLINED.

H	HI	D_p 0.25 (11)	0.25 D_p 0.50 (21)	D_p 0.50 (10)
500 m (10)	0.35 (7)	25,33	14,24,40	3,29
	0.35 (3)	27	28	32
500 to 1500 m (25)	0.35 (10)		4,22,26,35,36	5,21,31,37,38
	0.35 (15)	1,6,14	2,9,12,15,16, 18,34,39,41,42	17,23
1500 m (7)	0.35 (2)	11	20	
	0.35 (5)	7,8,19,30	10	

TABLE 4.6: VALUES OF SOME GEOMORPHOMETRIC PARAMETERS FOR SIX AREAS SELECTED FOR DETAILED ANALYSIS. VALUES FOR $\mathbb{R}$ ARE FROM CHAPTER 6, ALL OTHERS, FROM THIS CHAPTER.

	D_d	D_p	H	tan	$\mathbb{R}$	$\mathbb{H}$
8	0.555	0.102	1880	0.609	13.8	0.432
11	0.549	0.143	1709	0.395	8.1	0.260
18	1.847	0.286	833	0.396	7.4	0.547
24	0.631	0.383	203	0.065	0.25	0.286
31	0.290	0.553	1195	0.225	3.1	0.355
41	0.882	0.490	869	0.400	7.6	0.395

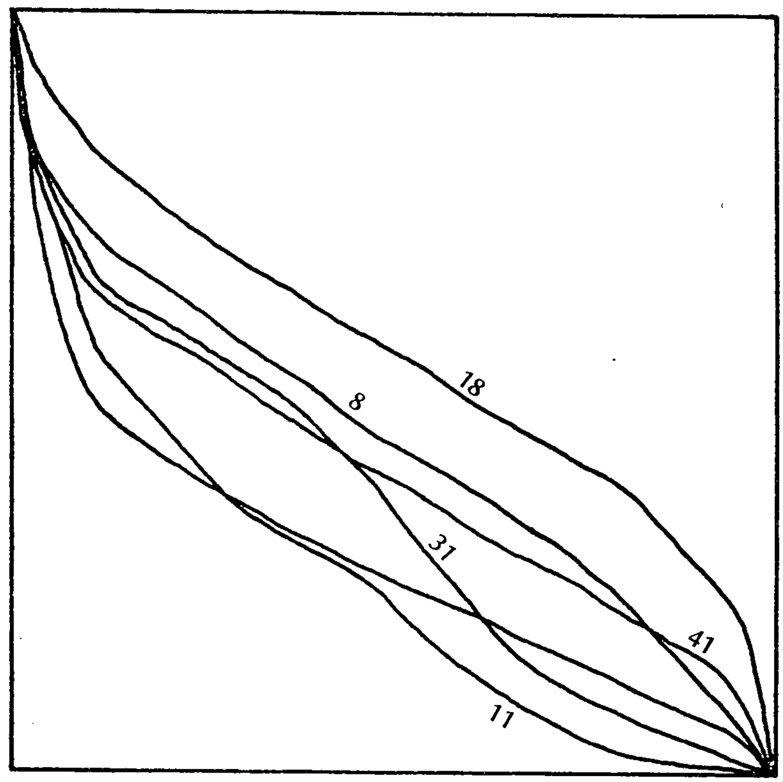


Figure 4.5: Hypsometric curves for the six terrain samples selected for detailed analysis.

peak just inside the western margin of the sample area. It is essentially an area of alpine glacial features -- the higher portions show such features as cirques (two of which contain small glaciers), horns, and aretes, with u-shaped glacial troughs between. Sample 8 had the highest local relief of the six areas selected for detailed analysis, and the fourth highest over all.

4.5.2: Sample 11: Ptarmigan Creek Map-area (83D/10W)

Sample 11 contains portions of three major physiographic subdivisions. The Rocky Mountain Trench, here only 1 to 1.5 km in width, cuts across the study area from northwest to southeast; it is occupied by the southeast-flowing Canoe River, whose elevation ranges from about 2300 to 2280 feet (701-695 m). To the northeast lies a portion of the Selwyn Range of the Rocky Mountains; the maximum elevation within the sample area north of the river is 7000 feet (2134 m) which occurs on an arete of an unnamed peak reaching 8048 feet (2453 m) just beyond the study area boundary. With the exception of the arete, the topography north of the Canoe River does not display the angularity characteristic of intense alpine glacial erosion. Such forms are present within the sample area in the Malton Range of the Monashee Mountains (a subdivision of the Columbia Mountains) which are found to the southwest of the Trench in this area. A horn with an elevation of 7888 feet (2404 m) represents the maximum elevation within the sample area. The topography of sample 11 is not unlike that of the previous one (sample 8), with its high relief and low peak density, but is distinguished by a considerably lower hypsometric integral (0.260) which is a result of a more prominent and level valley floor.

4.5.3: Sample 18: Manning Park Map-area (92H/2W)

This sample lies within the Hozameen Range of the Cascade Mountains. Once again, this sample area is dominated by forms produced by alpine-type glacial erosion. Here, however, the summits take on a more rounded appearance because they were overridden by ice during the last glacial maximum. Four summits within the area have elevations of about 6350 feet (1935 m), and most valley floors are around 4300 feet (1311 m). Only in the northwest corner, in the v-shaped valley of the upper Skagit River, does the surface descend below 4000 feet (1219 m) to the minimum elevation of 3450 feet (1052 m). Even so, the total relief of the area (833 m) is only "moderate", according to the divisions established in section 4.3.1; the hypsometric integral (0.547) is by far the highest of the six samples, and the fifth highest of the 42 areas.

4.5.4: Sample 24: Tatla Lake Map-area (92N/15E)

This sample lies near the western margin of the Fraser Plateau subdivision of the Interior Plateau. At 203 metres, this area has the lowest local relief of the 42 areas studied in this chapter. The area is primarily a drumlinized till plain produced by west-to-east moving ice (Tipper, 1971), with elevations of between 3100 and 3300 feet (945-1006 m); a major meltwater channel traverses the sample area leading into Tatla Lake itself, at 2985 feet (910 m) the minimum elevation in the area. This and another lake together cover some 4 per cent of the sample area. Five maxima, probably bedrock outcrops, rise above the till plain to altitudes of about 3650 feet (1113 m).

4.5.5: Sample 31: Ghitezli Lake Map-area (93E/9W)

This sample is also from the Interior Plateau, but from the Quanchus Range of the Nechako Plateau. The area contains Michel Peak, at 7396 feet (2254 m) the highest point in the Nechako Plateau region. The eastern (lower) boundary of the latter subdivision was defined by Holland (1964, p. 68) as the 3000 foot (914 m) contour, and since about 5 per cent of the present sample area is part of Glatheli Lake (elevation 3490 feet; 1064 m), the 7 by 7 km sample area contains almost the entire relief of the Nechako Plateau. Local relief for the study area (1190 m) is still only in the "moderate" class.

4.5.6: Sample 41: Oona River Map-area (103G/16W)

Sample 41 is from Porcher Island, and ranges from a maximum elevation of 2950 feet (899 m) at Egeria Mountain to a minimum of 100 feet (30 m) near Ogden Channel. The division between the Hecate Depression and the Kitimat Ranges of the Coast Mountains is not marked by any prominent physical feature in this area. Holland (1964, p. 35) stated that "the eastern boundary of the lowland is arbitrarily taken as a generalized line along the 2000 foot contour." Following this definition, the southwestern half of the sample area belongs to the Hecate Depression, the northeastern to the Coast Mountains; in fact, it is probably more appropriate to assign the entire sample area to a transition zone between the aforementioned physiographic divisions. The area displays many cirques, some with floors as low as about 500 feet (152 m), but nowhere are the ridges sharp as in, for example, the Illecillewaet map-area (sample 8). Probably, cirques were formed during an early "alpine" phase of glaciation, but later the entire area was overridden by ice. Cirques may or may not have been re-occupied by local ice after the disappearance of the Cordilleran ice sheet from the area.

Chapter 5: Procedures for Analysis and Theoretical Comparisons of Computer Systems

In this chapter, the analysis procedures used to estimate the geomorphometric parameters selected for special attention will be outlined. Of the seven variables examined in the last chapter, drainage and source densities were excluded from consideration for the reasons cited above. Peak density was excluded because of computational problems, especially because the correspondence between grid maxima and actual surface maxima may not be great. The remaining four parameters which are studied in this chapter are local relief (H), mean slope ($\tan \alpha$), roughness factor ($\mathbb{R}$), and hypsometric integral ($\mathbb{H}$). Theoretical errors involved in estimating the parameters from a triangular network of surface-specific points and from a regular grid will be discussed qualitatively, and in some cases quantitatively. Consideration will also be given to the theoretical relationships among these and related geomorphometric parameters, and to theoretical computer storage requirement. In the discussions which follow, it will be assumed that topographic maps provide the only available source of information about the topography.

5.1: Local Relief (H)

In estimating the "true" value of local relief from a contour map, errors can arise from a number of sources:

(1) map errors, which will be disregarded in the present discussion;

(2) interpolation errors -- the maximum possible interpolation error for both the highest and lowest point is one contour interval (expected error = 1/2 contour interval), and thus the maximum error in the local relief from this source is two contour intervals (expected error = one contour interval);

(3) errors due to misreading the contours -- this may be one contour interval, or even five contour intervals if an "index" contour is misread, for both the maximum and minimum point;

(4) errors due to the mis-identification of either the maximum or minimum point, or both -- for example, a particular summit may be taken to be the highest point within the study area when in fact a higher point exists.

Of these, (3) and (4) are "operator errors", and can be avoided by careful examination of the map and checking of the results; errors of types (1) and (2) are generally unavoidable, but are often small when compared to types (3) and (4).

5.1.1: Local Relief: Surface-specific Points

In both this and the grid method, the estimate of the local relief is the difference between the elevations of the highest and lowest sample points. All four of the sources of error for the "true" value of local relief listed above may contribute to error in the estimate of H obtained from a set of surface-specific points. "Type 4" errors should, however, be much less likely in the latter case than in a visual inspection of the contours. In digitizing an area using surface-specific points, an attempt is made to include all peaks and pits, as well as all maxima and minima long the borders of the area. If all are included, the true maximum and minimum elevations must be among them, and " type 4" errors are eliminated. If one assumes that no "avoidable operator errors" (types 3 and 4) are present in either case, the accuracy of this method should be equal to the "standard" method (visual inspection). Otherwise, the estimate of local relief obtained from a sample of surface-specific points should tend to be more accurate than that obtained from a visual inspection of the contours; of course, in any particular case, the errors from the various sources may combine to make the visual estimate closer to the true value.

5.1.2: Local Relief: Regular Grid

Considerably larger errors in estimating the minimum and maximum elevations result when a regular grid is used. As noted in section 2.2, grids are surface-random, and it is highly unlikely that a grid point will coincide with the true maximum or minimum elevation of the study area. Since the grid maximum cannot exceed the true maximum (unless there are interpolation errors) and the grid minimum will be greater than or equal to the true minimum, H*, the grid estimate of the relief, will be less than or equal to H. If γ is the average land slope near the maximum point, and c the distance from the maximum to the nearest grid point, the error in estimating the maximum should be given by:

$$e_{max} \cong c \tan \gamma \qquad (5.1)$$

A similar estimation may be made for e_{min}. As an estimate of the expected distance from an extreme point to the nearest grid point, one can use the root-mean-square distance (s_d) of all pints from the nearest grid point. If d is the grid spacing, and if the origin of the co-ordinate system is located at a selected grid point, s_d for all points closer to that grid point than to any other (i.e., within the inner box in Figure 5.1) is given by:

$$s_d = \left[\frac{1}{d^2} \int_{-\frac{d}{2}}^{\frac{d}{2}} \int_{-\frac{d}{2}}^{\frac{d}{2}} (x^2 + y^2)\, dy\, dx \right]^{\frac{1}{2}} = \left[\frac{d^2}{6} \right]^{\frac{1}{2}} = 0.408\, d \qquad (5.2)$$

One can further suppose that γ may approximately equal α, the mean ground slope; estimates of the errors in the maximum and minimum elevations would then be:

$$\hat{e}_{min} = \hat{e}_{max} = 0.408\, d \tan \alpha \qquad (5.3)$$

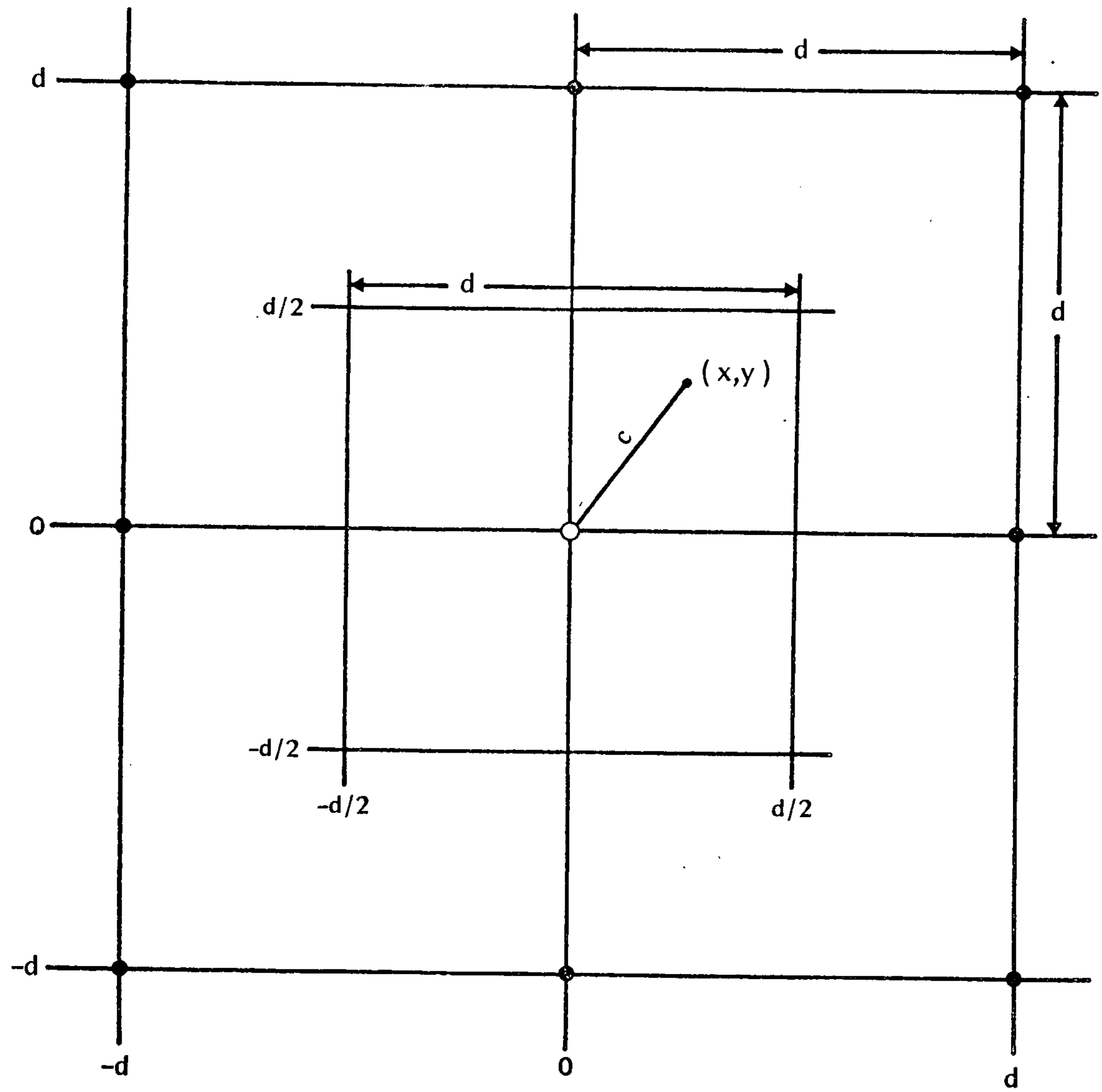


Figure 5.1: Illustration of the distance (c) from any point (x, y) to the nearest grid point (open circle). Solid circles indicate other grid points.

and thus the expected error in the value of the local relief would be:

$$e_H = 0.816 \text{ d } \tan \alpha \qquad (5.4)$$

The error in, and accuracy of, the grid estimate of the local relief is theoretically a linear function of the grid spacing, as proposed by the "sampling theorem" (see section 2.2). Of course, the mean slope (α) may not be a good estimate of the land slope near the extreme point. In many of the areas examined in section 4.3, the minimum elevation was on a lake, the sea, or a floodplain, and the slope near this point (and thus also e_{min}) was near zero. Slopes near the maxima and the minima of most of the forty-two samples from Chapter 4 (grid spacing 1 km) were estimated by dividing the elevation differences between the points and the nearest grid points by the horizontal distances; these values should approximate tan γ. The mean values of these angles for the maxima are similar to tan α, in particular cases they may differ by a factor of two or more; average slope near the <u>minima</u> is only about one third of the mean slope. As an added complication, the closest grid point to the maximum may not be the highest grid point, and the same may hold for the minimum. In such cases, the error in the grid estimate may not be as great as expected. The empirical relationship between e_H and tan for the forty-two samples from Chapter 4 was

$$e_H = 234.1 \tan \alpha + 63.12 \; (r^2 = 0.245) \qquad (5.5)$$

where e_H is in metres and d is 1000 m. This relationship is statistically significant (95 per cent level); the large amount of "unexplained" variance is probably a result of the random factor of the actual distance from the extreme points to the nearest grid points, and of the difference between tan γ and tan α. The ratio of the mean values of e_H and tan α, divided by d (1000 m) is 0.426, still only about half of the theoretical coefficient (equation 5.4).

This is probably because the slope near the minimum was often much less than the mean slope, and because in some cases the highest (or lowest) grid point was higher (or lower) than the grid point closest to the true maximum (or minimum).

5.1.3: Review

In summary, the estimate of the local relief obtained from a set of surface-specific points should be as accurate as, or even more accurate than, the estimate obtained through a visual inspection of the contours. For regular grids, errors due to the fact that it is very unlikely that a grid point will coincide exactly with the minimum or maximum point will tend to be much larger than interpolation errors. It would appear that the error in estimating H from a grid will average about $0.4\ d \tan\alpha$, which could be large in areas of steep slopes if a relatively wide grid spacing is used. Surface-specific points should theoretically provide much better estimates of local relief than should regular grids of "reasonable" densities. Relief error for a given average slope should be a linear function of grid spacing.

5.2: Mean Slope ($\tan\alpha$)

Strahler (1956) determined the "true" mean and standard deviation for slopes in drainage basins by measuring slope tangent at a large number of points, drawing lines of equal slope tangent (isotangents), and using a planimeter to determine the relative frequencies of the various slope classes. Means and other distributional parameters were then determined from these frequencies. Strahler then showed that the distribution of slope measurements at 100 randomly-located points within one study area was not significantly different from the "population" values. As noted earlier (section 3.4.2), Griffiths (1964) compared this "point sampling" method to the "traverse sampling" method (Wentworth, 1930) and a "subjective" method similar to that described by Raisz and Henry (1937).

He concluded that the Wentworth method produced the most accurate results of the three. The "isotangent" method would probably produce the best results, but as this is very time consuming, as Strahler concluded that the results of point sampling were not significantly different from this, and as Griffiths concluded that the Wentworth method was superior to the point sampling approach, the Wentworth method was used herein to provide an estimate of the "true" mean slope to which computer values will be compared in the next chapter.

5.2.1: Computational Procedures

For the mean slope and for the subsequent two geomorphometric measures, the regular grids were first converted to a set of continguous triangular facets by inserting one set of diagonals into the grid; the same analysis procedures were then used for both these triangles and the triangles based on the surface-specific points. For each triangle, a vector orthogonal to it was determined by computing the cross product of vectors forming two edges of the triangle. The length of this vector is twice the true area of the triangle, while the z-component of the orthogonal vector is twice the projected (map) area. Unit orthogonal vectors were determined by dividing the components by the total length, and the slopes of the triangles were computed from the z-components of these unit vectors. Three average slopes, namely unweighted, weighted by map area, and weighted by true area, were determined. While the latter may represent the most logical weighting (cf. Evans, 1972, p. 37), map area has been used by most methods, including the Wentworth approach discussed above.

The accuracy of the mean slope estimate obtained from a set of triangles is highly dependent upon how closely the triangles approximate the surface. In the case of surface-specific points, the accuracy will depend upon the selection of the points and the size of the triangles. Pillewizer (1972) noted that the triangle method, as applied by Hormann (1971), failed to indicate a slope asymmetry detected by field surveys and careful analysis of large-scale topographic maps. Pillewizer attributed this failure to the fact that Hormann's triangles were too large. For triangles derived from a grid, there will be no control over the degree to which the triangles approximate the surface, except through the size, which is a function of grid spacing.

5.3: Roughness Factor ($\mathbb{R}$)

As pointed out in section 3.5, the roughness factor is closely related to the inverse of k, Hobson's (1967, 1970) vector dispersion factor. The latter is defined only for unit vectors, and it was argued in section 3.5 that even for grids, it would be better to weight the vectors by the true areas of the triangles. In the grid case, the map areas of all triangles are equal, and the use of unit vectors (cf. Hobson) should not produce results which differ greatly from weighted vector analysis. For the latter, steeper triangles will be weighted more, increasing the roughness factor slightly. For triangles based on surface-specific points, the use of unit vectors will be inappropriate, since the sizes of the triangles may vary considerably. In this study, both weighted and unweighted analyses were conducted, using the orthogonal vectors noted above. The only "standard" roughness value to which other methods might be compared would be Hobson's k (or its inverse), but as proposed in section 3.5, this measure should be inferior to the value of $\mathbb{R}$ obtained from a weighted vector analysis based on surface-specific points. Thus no useful comparisons of the computer estimates to "true" values can be made as for the preceding parameters.

5.4: Hypsometric Integral ($\mathbb{H}$)

The "true" value of the hypsometric integral was determined by using a planimeter to measure the areas above various elevations (that is, enclosed within selected contours); the elevations are converted to relative values by subtracting the minimum height and dividing by the local relief, while relative areas are computed by dividing by the total area. These points can be plotted to produce hypsometric curves (see Figure 4.5), and the hypsometric integrals can then be determined by measuring the areas under the curves with a planimeter, or by determining the integrals mathematically. In this study, the latter approach was used, employing the trapezoidal method for integrating a function whose values are known at a set of points.

Most research using the hypsometric integral has involved drainage basins as basic units, although some studies have applied this measure to arbitrarily-bounded topographic samples as are used in the present work (cf. Gassmann and Gutersohn, 1947; Wood and Snell, 1960; Pike and Wilson, 1971; Evans, 1972). None of these works, however, recognized or commented upon the fact that the shape and orientation of the sample area may influence the form of the curve and sometimes the value of the integral, or that the hypsometric integral for a group of basins may not equal the mean of the basin values. The former fact can be illustrated by applying a square sample area with two different orientations and a circle to two simple geometric forms: an inclined plane, and a square-based pyramid considerably larger than the sample area with the latter centred at its apex. For the inclined plane, the hypsometric integral for all three samples is 0.5, but the forms of the curves differ (see Figure 5.2); the circle and the "diagonal square" (the square with a diagonal parallel to the dip of the plane) produce "s-shaped" curves which Strahler (1952) noted were characteristic of higher-order drainage basins at the equilibrium stage in the absence of structural control. Many such basins have outline forms similar to the circle or the diagonal square, and the "characteristic s-shape" is probably in part due to the influence of outline form. In the case of the pyramid, both the curve form and the hypsometric integral vary with the shape and

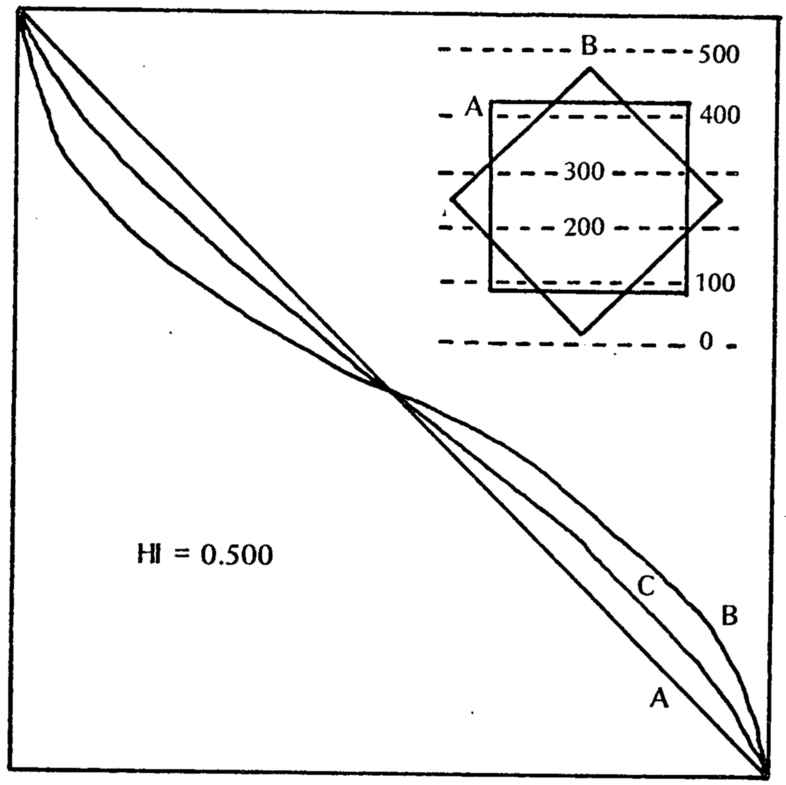


Figure 5.2: Hypsometric curves for the portions of an inclined plane within 3 sample areas.

A: "parallel" square (see inset, A);

B: "diagonal" square (see inset, B);

C: circle.

orientation of the sampling area (Figure 5.3). Indeed, the curve and integral are identical for the plane and the pyramid in the case of the diagonal square sampling areas. This effect could produce considerable variation in results if the size of the sampling area is less than or equal to the "texture" of the topography in an area. In the present study, however, the sample areas (7 by 7 km) are considerably larger than the topographic texture of these areas.

The second consideration in the case of arbitrarily-bounded sample areas is the relationship between the hypsometric integral for such an area and the integrals of its constituent drainage basins. As a simplified illustration, one can consider two adjacent basins of equal areas, minimum elevations of zero, and hypsometric integrals of 0.5 -- the only difference is that one basin has a local relief of 500 m, the other 1000 m. The former basin will have a mean elevation of 250 m, the latter 500 m -- the mean elevation of the combined basins will be 375 m. The total relief is 1000 m, and thus the hypsometric integral of two basins will be 0.375, twenty-five per cent less than that of either of the individual basins. Other combinations of relative reliefs, minima, areas and integrals can produce hypsometric integrals for combined basins larger than those of the constituent basins. If the minima and hypsometric integrals are equal, as will be approximately the case in "equilibrium" topography with a common local base level (the ocean, a lake, or a low-gradient floodplain), the aggregate integral will always be less than the individual ones. This may in part explain the relatively large number of the forty-two areas examined in Chapter 4 which had overall integrals below the lower limit of "equilibrium" (0.35) proposed by Strahler (1952) for individual basins.

As noted above, the regular grids were converted to sets of triangles and analyzed using the same methods as employed for triangles based on surface-specific points. It can be easily shown that the volume between a triangular

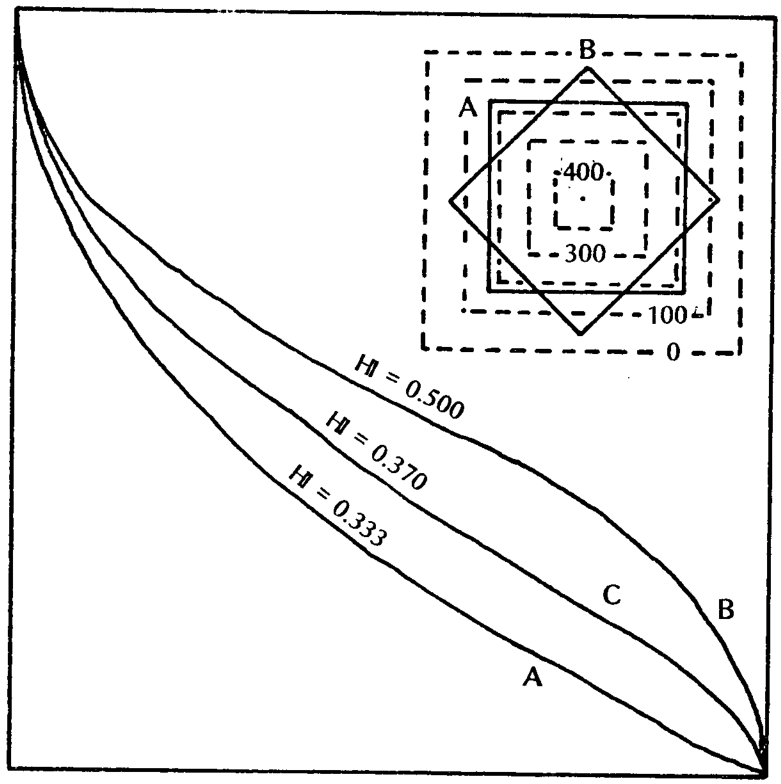


Figure 5.3: As in Figure 5.2, but for a square-based pyramid. Here, the hypsometric integral varies as well as the curve form.

plane and the horizontal datum plane is equal to the product of the projected area of the triangle and the mean elevation of the three corners of the triangle. These volumes can be summed and divided by the total area to give the mean elevation of the study area. This can then be used in the elevation-relief ratio formula (equation 3.14) to estimate the hypsometric integral.

5.4.1: Hypsometric Integral: Surface-specific Points

It is difficult to determine quantitatively the theoretical precision of this method. The degree to which the value of HI determined as described above from a set of surface-specific points approximates the true value will depend upon how closely the land surfaces within the triangles formed from these points approximate planes. If the person selecting the points is careful to make sure that the contours within each triangle are approximately parallel and equally spaced, the method should be reasonably accurate.

5.4.2: Hypsometric Integral: Regular Grid

The mean elevation determined from triangles based on a regular grid using the volumetric method outlined above will be very close to the arithmetic mean of the sampled elevation values. Each point not on the outer boundary forms a vertex of exactly six triangles, and thus all such points are equally weighted (the projected areas of the triangles are, of course, equal); points along the boundaries are in three triangles, while corner points are in one or two. Since no attempt is made to ensure that the areas within each triangle are even approximately planar, the estimate of the mean elevation derived from the grid should not be as accurate as that obtained from a set of surface-specific points. The principal sources of error, however, are errors in the maximum and minimum elevations used in the elevation-relief ratio formula (equation 3.14), errors which have been discussed above in section 5.1.2. In the following discussion, e_{max} and e_{min} are non-negative error terms, and an asterisk (*) is used to denote values determined from the grid alone. If one defines:

$$z^*_{max} = z_{max} - e_{max} \tag{5.6}$$

$$z^*_{min} = z_{min} + e_{min} \tag{5.7}$$

and

$$HI^* = \frac{\bar{z} - z^*_{min}}{z^*_{max} - z^*_{min}} \tag{5.8}$$

It follows that:

$$HI^* = \frac{\bar{z} - (z_{min} + e_{min})}{(z_{max} - e_{max}) - (z_{min} + e_{min})} \tag{5.9}$$

Some algebraic manipulation of this equation yields:

$$HI^* \left[1 - \frac{e_{max} + e_{min}}{z_{max} - z_{min}}\right] + \left[\frac{e_{min}}{z_{max} - z_{min}}\right] = \frac{\bar{z} - z_{min}}{z_{max} - z_{min}} \tag{5.10}$$

The right-hand-side of this equation is the true value of the hypsometric integral (disregarding possible errors in $\bar{z}$), and $z_{max} - z_{min}$ is H, the true local relief, giving:

$$HI = HI^* \left[1 - \frac{e_H}{H}\right] + \frac{e_{min}}{H} \tag{5.11}$$

If HI* is to be accurate, HI* must equal HI, in which case either e_H must equal zero or the following relationship must hold true:

$$HI = HI^* = \frac{e_{min}}{e_H} \tag{5.12}$$

The latter ratio may provide a rough estimate of hypsometry, since for the 42 samples examined in Chapter 4 it was significantly correlated with HI, although the r^2 value was only 0.345.

Some further re-arrangement of equation 5.11 yields the following expression for the relative error in HI*:

$$e_{HI} = \left| \frac{HI - HI^*}{HI} \right| = \left| \frac{e_{max} - e_{min} \left[\frac{1 - HI}{HI} \right]}{H^*} \right| \qquad (5.13)$$

Equations 5.12 and 5.13 imply that if the hypsometric integral is low, the error in the minimum elevation must be less than that in the maximum if HI* is to be a good estimate of **H**. In fact, a low hypsometric integral generally implies gentler slopes near the minimum elevation than near the maximum (see section 3.6.1), which in turn implies that e_{min} will be less than e_{max} (see section 5.1.2). For high values of **H**, e_{min} must exceed e_{max} to minimize the error in the grid estimate of the hypsometric integral, and again this will be the "expected" result. The dependence in part of these error terms upon HI should result in errors in HI* being somewhat less than equation 5.13 suggests.

An attempt was made to determine the relationship between the grid spacing (d) and the theoretical errors in the hypsometric integrals for a square-based pyramid for grids parallel and diagonal to the pyramid base. The grids had odd numbers of rows and columns and were centred on the pyramid apex; meaning that e_{max} was zero. When the grid minimum was used in the calculations, e_{HI} was found to be a linear function of d, once again supporting the "sampling theorem" noted in section 2.2; when the "true" minimum was used, the error was proportional to d^2. To halve the error in the former case would require four times as many points, but in the latter only twice as many.

5.4.3: Summary

It is difficult to assess quantitatively the theoretical accuracy of the estimate of the hypsometric integral obtained from a set of surface-specific points. Accuracy will depend upon how closely the triangles formed by these points approximate the land surface. For regular grids where only the grid points are used, the error in HI should tend to be a linear function of the grid spacing (d), and is sensitive to the values of e_{max} and e_{min} (equation 5.13).

5.5: Possibility of Estimating Other Parameters

In addition to the four measures discussed above, many more of the geomorphometric parameters reviewed in Chapter 3 might be estimated from computer-stored terrain information. Among the most useful of these would be the measures of texture or grain outlined in section 3.2. Most of these measures depend upon the density of peaks, pits, streams, or ridges, and are thus strongly related to surfac-especific points and lines. It should be possible to estimate these parameters rather readily from a set of surface-specific points; in the case of grids, the same approach might be applied, but many "false" peaks and pits will appear in such data, simply because a grid point which falls on a ridge may be surrounded by grid points on the sides of the ridge and thus appear to be a "peak" when in fact it is not. The definition of peaks, pits, ridges, and courses will theoretically be much easier if surface-specific points are stored in the "pointer mode", rather than the "triangle mode" used in the present study (see section 2.6). For example, a peak is defined as any point which is higher than all its neighbours; the neighbours must therefore be known before elevation comparisons can be made. Once the number of peaks or pits, or the total length of ridges or courses, is established, it can be used to compute peak or pit density, ridginess (cf. Speight, 1968) or drainage density. It would also be possible to compute other roughness measures (cf. Hobson, 1967, 1972), distributional parameters for the vectors orthogonal to the land surface other than $\mathbb{R}$ or k, or measures of slope asymmetry (cf. Hormann, 1971, section 4.2.4).

5.6: Theoretical Numbers of Points and Triangles for Triangular Data Sets, and Theoretical Computer Storage Requirements

"Euler's Law" for a contiguous set of N_C cells, N_E edges and N_V vertices states that:

$$N_V + N_C - N_E = 1 \qquad (5.14)$$

if the "outside" is not considered to be a cell. If all cells are triangles, there should be $3N_C$ sides. Since all edges form sides of two triangles with the exception of those edges forming the outer boundary of the study area, the total number of edges is given by:

$$N_E = \frac{3N_C + N_B}{2} \qquad (5.15)$$

where N_B is the number of edges (and also the number of vertices) which form the boundary. Substituting this value in equation 5.14 and solving for N_C yields:

$$N_C = 2N_V - (N_B + 2) \qquad (5.16)$$

Thus the total number of triangles in a data-set will be somewhat less than twice the number of points.

One can determine the theoretical computer storage requirements of the regular grid, and of the "pointer mode" and "triangle mode" of the triangular data-set method. Each integer value requires one half-word of computer storage allocation, while each "real" or decimal value requires a full word. To store the three co-ordinates (reals) and the identification number (integer) of a surface-specific point would thus require 7 half-words of computer space, while each grid point needs only 2 half-words of computer storage. For the surface-specific points, either a set of pointers or a set of triangles must also be stored. The total number of pointers in a data-set will be twice the number of edges (N_E), since each edge forms a pointer of each of the vertices at its ends. Using equations 5.15 and 5.16, the total average requirements for the pointers of a data-set can be shown to be $(6N_V - 2(N_B + 3))$ half-words, and the total storage for the points and pointers is given by

$$(13N_V - 2N_B - 6) \text{ half-words} \qquad (5.17)$$

For the "triangle mode", there are required 3 half-words for each triangle, the number of triangles being given by equation 5.16. The total storage requirements for the points and triangles should equal:

$$(13N_V - 3N_B - 6) \text{ half-words} \qquad (5.18)$$

which is exactly N_B less storage space than needed by the "pointer mode".

Chapter 6: Empirical Comparisons and Computational Results

In this chapter, the results of an empirical comparison of the two computer terrain storage methods discussed above will be reported. To provide data for the comparison, the analysis procedures outlined in Chapter 5 were applied to the six topographic samples described in section 4.5, for both 15 by 15 grids (d = 500 m) and sets of surface-specific points. Figure 6.1 shows one of the surface-specific point data-sets; maps of the other data-sets are given in Appendix IIIb. Samples 11 and 18 were arbitrarily selected to investigate the reproduceability of triangular data-sets and the influences of triangle size and map scale. Each of the regular grids was analyzed twice, using first northwest-southeast and then northeast-southwest diagonals. The results of all the computer analyses conducted are given in Appendix IIIc.

For the six sample areas, the differences between the computer estimates and the "standard" estimates for local relief, mean slope, and hypsometric integral were determined. For each method, the mean and standard deviations of the "errors" were determined, and the t-statistic was used to test the probability that the true mean error of each method was zero. If for any method this probability was 5 per cent or less, it would be concluded that the method of estimating the parameter being tested was not valid. The mean errors for the grids and triangular data-sets were compared, and the assumption that grid error is proportional to grid spacing was used to estimate the grid density which would be required to produce the precision achieved by the triangular data-sets. The hypothetical digitization times and computer storage requirements of these hypothetical grids were then compared with those of the triangular data-sets using the time and storage estimates developed in the following section.

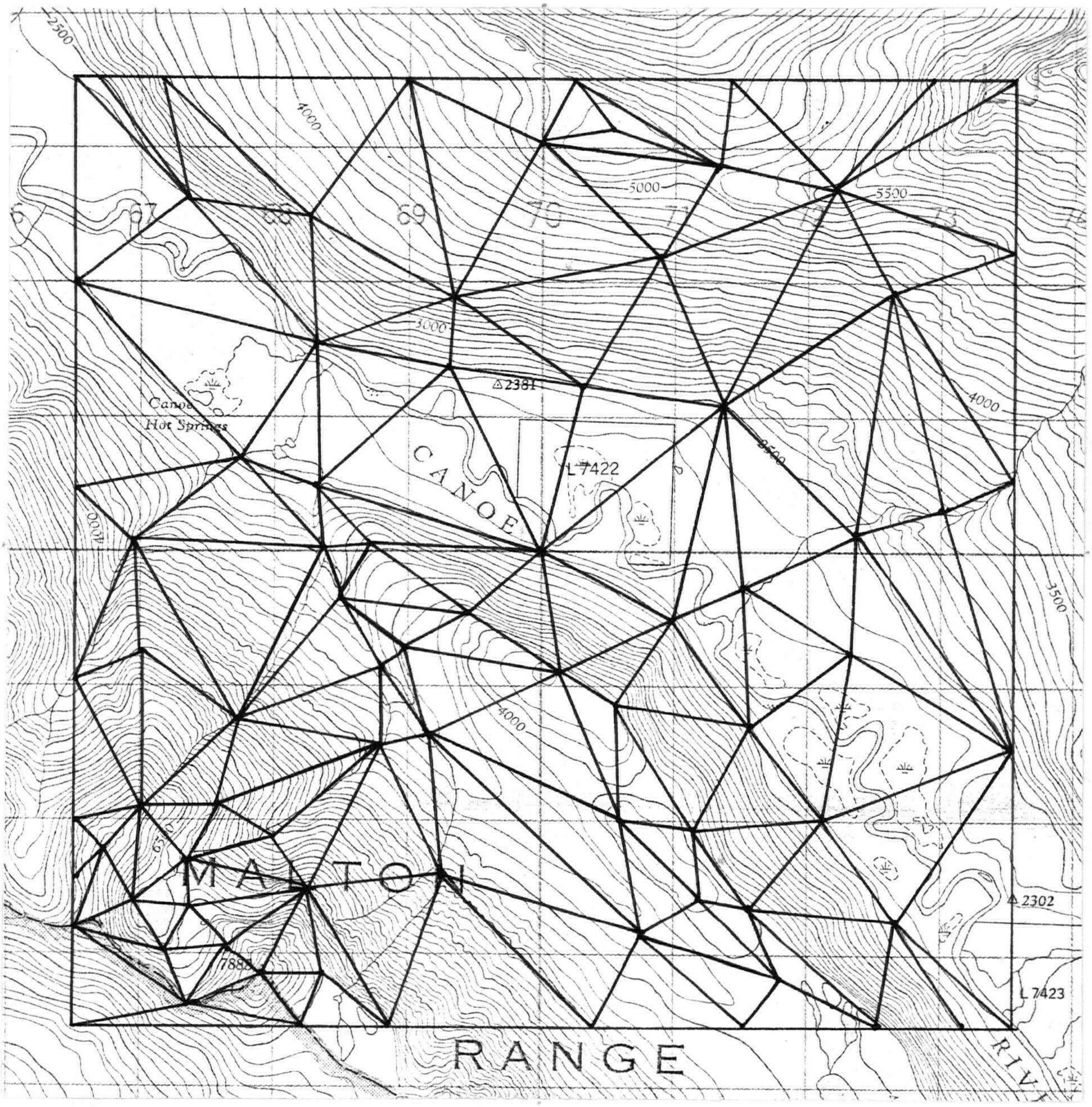


Figure 6.1: Sample 11a, an example of a triangular data-set from the Ptarmigan Creek map-area.

6.1: Digitization Time and Computer Storage

Table 6.1 gives the numbers of points, boundary points, and triangles for the sets of surface-specific points used in this study. These all conform to the theoretical relationship given in equation 5.16.

Tests were made of the lengths of time needed to obtain the data from the topographic maps. For data to be punched on computer cards, the times cited are those required to first record the data values on a tape recorder and to then play back the tapes, writing the values on computer coding forms. The average time required to determine the elevation of a point was found to be 8.3 seconds -- this should be the same for both surface-specific points and grid points. Drawing the triangular data-sets and numbering the points and triangles required 8.3 seconds per point, while an average of 8.0 seconds was needed to determine the vertices of each triangle. Measuring the x and y co-ordinates used an average of 12.6 seconds per point, but it should be possible to improve this considerably by using a digitizer.

Table 6.1 indicates that the average triangular data-set analyzed herein contained 114 points and 197 triangles. Digitization of such a data-set would theoretically require 946 seconds to draw the triangles, 1576 seconds to determine the vertices of these triangles, and 2382 seconds to digitize the points, a total of 4904 seconds, or 43.0 seconds per point. For grids, only the elevations must be determined, and the 15 by 15 grids (225 points) should require an average of 1867 seconds. This means that the triangular data-sets required about 2.6 times as long to prepare as did the grids. The use of a digitizer in determining locational co-ordinates of surface-specific points should reduce this ratio somewhat.

Equation 5.18 implies that the average triangular data-set stored in the "triangle mode", would require 1389 half-words of computer storage allocation;

TABLE 6.1: NUMBERS OF POINTS (N_V), BOUNDARY POINTS (N_B) AND TRIANGLES (N_C) FOR DATA-SETS ANALYZED

sample	N_V	N_B	N_C
8	90	25	153
11a	81	24	136
18a	119	29	207
24	142	32	250
31	114	28	198
41	138	34	240
means	114	29	197
11d	85	25	143
11b, c	29	15	41
18b, c	25	16	32

the grids would require but 450 half-words. The surface-specific point data-sets thus require about 3.1 times as much computer storage space as the grids.

6.2: Local Relief (H)

Table 6.2 presents the estimates of local relief obtained from a visual inspection of the contours ("standard method"), from the 7 by 7 grids (d = 1000 m) used in Chapter 4, and from the computer analyses of the 15 by 15 grids and the triangular data-sets. The results confirm those derived theoretically in section 5.1 -- the triangular data-sets produce results very similar to the visual inspection method, while grid errors may be rather large. Theoretically, relief error should be a linear function of the grid spacing (d). For the six samples given here, the ratio of grid errors was somewhat less than one third when it should in theory be one half. The difference may be fortuitous due to the random factor of distance from the extrema to the nearest grid points which influences the grid error, and to the small sample size.

The t-tests indicated that none of the average errors were significantly different from zero, given the small sample size. Paired t-tests were used to determine whether the errors of the three estimates were significantly different from each other. All three pairs were significantly different at the 95 per cent level, meaning that while the grid estimates were not "significantly bad", the triangular data-sets produced errors significantly less than those of the grids.

6.3: Mean Slope (tan α)

The results of slope estimation using four methods are given in Table 6.3. Here, the value obtained using the line intersection method of Wentworth (1933) is the "standard" to which the computer estimates are compared (see section 5.2). Once again, the t-tests indicated that none of the mean errors differed significantly from zero. Paired t-tests showed that the triangle and grid estimates were

TABLE 6.2: ESTIMATES OF LOCAL RELIEF (H), AND ANALYSIS OF ERRORS IN THESE ESTIMATES

sample	standard method	7 x 7 grid	15 x 15 grid	triangular data-set
8	1880	1655	1853	1865
11	1709	1590	1606	1709
18	883	619	823	787
24	203	184	187	203
31	1195	1057	1192	1195
41	869	752	823	869
error (e):				
8	-	225	27	15
11	-	119	103	0
18	-	264	60	5
24	-	19	16	0
31	-	138	3	0
41	-	117	46	0
$\bar{e}$		147	42.5	3.3
s_e		87	36.0	6.1
t		0.689	0.482	0.224
$p\ (\bar{e} = 0)$		52%	66%	82%

TABLE 6.3: ESTIMATES OF MEAN SLOPE (tan α), AND ANALYSIS OF ERRORS IN THESE ESTIMATES

sample	Wentworth method	15 x 15 grid NW-SE	15 x 15 grid NE-SW	triangular data-set
8	0.609	0.523	0.518	0.585
11	0.395	0.344	0.358	0.355
18	0.396	0.331	0.335	0.393
24	0.063	0.041	0.039	0.048
31	0.218	0.187	0.185	0.203
41	0.400	0.324	0.336	0.381
error (e):				
8	-	0.086	0.091	0.024
11	-	0.051	0.037	0.040
18	-	0.065	0.061	0.003
24	-	0.022	0.024	0.015
31	-	0.041	0.033	0.015
41	-	0.076	0.064	0.019
$\bar{e}$		0.055	0.051	0.019
s_e		0.025	0.025	0.012
t		0.896	0.843	0.639
$p\ (\bar{e} = 0)$		42%	44%	56%

significantly different. As expected, the two slope estimates obtained from the same grid using different diagonals were not significantly different at the 95 per cent level.

6.4: Roughness Factor (R)

As noted earlier in section 5.3, there exists no useful "standard" value of the roughness factor to which computer estimates can be compared. Table 6.4 presents the results of unit vector analysis of grids (the method used by Hobson, 1967, 1972, and by Turner and Miles, 1967), of weighted vector analysis of grids, and of weighted vector analysis of triangular data-sets. The similarity of columns 1 and 2 (also of 3 and 4) in the Table supports Turner and Miles' contention that the orientations of the diagonals used to form the triangles has little effect on the results. In the absence of a standard value, the claim made above in Chapters 3 and 5, that the weighted analysis of triangular data-sets should yield the best results, cannot be substantiated empirically. The five sets of values given in Table 6.4 were not significantly different from each other.

6.5: Hypsometric Integral (HI)

Table 6.5 presents the results of hypsometric analysis of the six study areas using six different methods. The standard values were obtained through the use of a polar planimeter, while the second and third columns report results obtained from grids in Chapter 4. HI, based on the best available estimates of the minimum and maximum elevations, follows the approach recommended by Pike and Wilson (1971); HI*, as well as the results for the 15 by 15 grids, used the grid estimates of these quantities. Pike and Wilson claimed (p. 1081) that 40 to 50 points will generally produce results within 0.01 of the true values. This claim is supported by the fact that the mean error produced by their method is 0.006, and in none of the six cases did the error reach 0.01.

TABLE 6.4: ESTIMATES OF ROUGHNESS FACTOR ($\mathbb{R}$)

sample	15 x 15 grid unit vectors NW-SE	NE-SW	weighted vectors NW-SE	NE-SW	triangular data-set
8	11.36	11.23	11.90	11.85	13.80
11	6.76	6.93	7.23	7.29	8.12
18	5.75	5.79	5.96	5.97	7.37
24	0.13	0.13	0.14	0.13	0.24
31	2.27	2.26	2.44	2.43	2.92
41	5.80	5.82	6.10	6.11	7.61
means	5.35	5.36	5.63	5.63	6.68

TABLE 6.5: ESTIMATES OF HYPSOMETRIC INTEGRAL (HI), AND ANALYSIS OF ERRORS IN THESE ESTIMATES

sample	standard method	7 x 7 grid HI	7 x 7 grid HI*	15 x 15 grid* NW-SE	15 x 15 grid* NE-SW	triangular data-set
8	0.432	0.428	0.479	0.436	0.436	0.447
11	0.260	0.265	0.284	0.279	0.281	0.263
18	0.547	0.546	0.429	0.566	0.567	0.542
24	0.278	0.271	0.258	0.289	0.297	0.268
31	0.338	0.334	0.278	0.334	0.334	0.337
41	0.395	0.403	0.371	0.420	0.420	0.404
	error (e):					
8	-	0.004	0.047	0.004	0.004	0.015
11	-	0.005	0.024	0.019	0.021	0.003
18	-	0.001	0.118	0.019	0.020	0.005
24	-	0.007	0.020	0.011	0.019	0.010
31	-	0.004	0.060	0.004	0.004	0.001
41	-	0.008	0.024	0.025	0.025	0.009
$\bar{e}$		0.006	0.049	0.014	0.015	0.007
s_e		0.002	0.038	0.010	0.010	0.005
t		0.795	0.529	0.559	0.622	0.557
p ($\bar{e}$ = 0)		46%	62%	60%	56%	60%

* these estimates are based on grid values only

The best of the computer estimates, those based upon the triangular data-sets, had a slightly larger average error, with the grid estimates considerably poorer.

As in the cases of local relief and slope, the t-tests indicated that none of the mean errors differed significantly from zero. Unlike those parameters, however, only one of the 10 paired t-tests indicated a marginally significant difference in average errors -- that was between Pike and Wilson's method and the estimate obtained from the 15 by 15 grids using the northeast-southwest diagonals.

6.6: Comparison of Errors for Triangular Data-sets and Grids

In Tables 6.2, 6.3, and 6.5, the errors in estimating local relief, mean slope, and hypsometric integral using both regular grids and triangular data-sets were given. Table 6.6 repeats these error values and gives the ratios between the estimate errors for the two methods. According to the "Sampling Theorem" introduced in section 2.2, error should be proportional to the grid spacing and the relationship should be linear. This was confirmed theoretically for two of the above three parameters in Chapter 5. If this is applied to the grid errors noted above, one finds that in order to reduce the grid error in the estimation of local relief to the level of precision achieved by triangular data-sets, one would need to reduce the grid spacing from 500 m to 39 m. This and the values for the other two parameters are listed in Table 6.6, as are other characteristics of these hypothetical grids. Finally, the values developed above in section 6.1 are used to estimate the relative digitization times and computer storage allocation requirements of these grids compared with those of triangular data-sets. For all three parameters, it appears that a given level of precision can be attained with less digitization time and computer storage space using surface-specific points than using regular grids. The contrast is much more dramatic for local relief than it is for the other two parameters.

TABLE 6.6: EMPIRICAL COMPARISON OF ERRORS FOR TRIANGULAR DATA-SETS AND 15 BY 15 GRIDS

	H	tan α	HI
Mean errors:			
15 x 15 grids	42.5	0.053	0.015
triangular data-sets	3.3	0.019	0.007
ratio	12.9	2.8	2.1
Characteristics of grids theoretically required* to produce same precision as triangles:			
d (metres)	39	179	234
grid size	181 x 181	40 x 40	31 x 31
# of grid points	32,761	1,600	961
Ratios of requirements of such grids to those of triangular data-sets:			
digitization time	55.4	2.7	1.6
storage space	47.2	2.3	1.4

* assuming a linear relationship between grid error and grid spacing

6.7: Reproduceability and the Influence of Scale

As noted above, samples 11 and 18 were selected to investigate the influence of scale. For each area, an additional data-set was derived from a 1:250,000 scale map of the same area (samples 11b, 18b); next, approximately the same points were located on 1:50,000 scale maps (11c, 18c). Sample 11 was also used to examine the reproduceability of triangular data-sets by producing another such data-set of that area (sample 11d) with approximately the same number of points as sample 11a. The number of points and triangles in all of these data-sets were given in Table 6.1. In separate analyses of samples 11 (Table 6.7) and 18 (Table 6.8), values of the four selected parameters were standardized, and the distances between sub-samples in the resulting four-variable "phase space" were calculated. For sample 11, the most similar pair was a and d, the two with similar numbers of points and triangles derived from the same map. Next were the distances between these and sub-sample c, derived from the same scale of map but using many less points and triangles. The most "different" data-set was 11b, derived from a smaller-scale map with a larger contour interval. It seems that for this area, map scale differences are more important than the number of triangles used. For area 18 (Table 6.8), the opposite conclusion was reached. In this case, the most similar pair was b and c, the two sub-samples with similar and lesser numbers of points derived from maps of different scales. The greatest difference was between a and b, which were from different maps and which also used different numbers of points and triangles. It would appear that for area 18, the number of triangles, or perhaps more correctly the mean size of the triangles, is more important than the differences between the 1:50,000 and 1:250,000 scale maps. Because the triangles in 18b and 18c were too large, the topography was smoothed and slopes reduced (see **R** and tan α values in Table 6.8).

TABLE 6.7: SIMILARITY AMONG FOUR TRIANGULAR DATA-SETS BASED ON SAMPLE 11 FOR THE FOUR SELECTED MEASURES

	H	HI	tan α	R	numbers of points	numbers of triangles
Original values:						
a	1709	0.263	0.355	8.12	81	136
b	1661	0.285	0.378	8.07	29	41
c	1709	0.265	0.367	7.59	29	41
d	1709	0.262	0.371	8.31	85	143
mean	1697	0.269	0.368	8.02		
s	24	0.011	0.008	0.306		
Standardized values:						
a	0.500	-0.550	-1.684	0.326		
b	-1.500	1.467	1.295	0.163		
c	0.500	-0.367	-0.130	-1.404		
d	0.500	-0.642	0.389	0.947		
Inter-pair differences:					distance*	rank
a-b	2.000	2.017	2.979	0.163	4.119	(6)
a-c	0.000	0.183	1.554	1.730	2.333	(2)
a-d	0.000	0.092	2.073	0.621	2.166	(1)
b-c	2.000	1.834	1.425	1.567	3.442	(5)
b-d	2.000	2.109	0.906	0.784	3.144	(4)
c-d	0.000	0.265	0.519	2.351	2.422	(3)

* this is the distance between the samples in the four-dimensional space whose axes are the four variables

Sub-samples: a, d -- 1:50,000 scale, small triangles;
b -- 1:250,000 scale, large triangles;
c -- 1:50,000 scale, large triangles.

TABLE 6.8: SIMILARITY AMONG THREE TRIANGULAR DATA-SETS BASED ON SAMPLE 18 FOR THE FOUR SELECTED MEASURES

	H	HI	tan α	R	numbers of points	numbers of triangles
Original values:						
a	878	0.542	0.397	7.39	119	207
b	838	0.517	0.257	3.45	25	32
c	823	0.544	0.295	4.53	25	32
mean	846	0.534	0.316	5.12		
s	28	0.015	0.072	2.037		
Standardized values:						
a	-1.126	-0.532	-1.119	-1.114		
b	0.281	1.130	0.290	0.820		
c	0.809	-0.665	0.815	0.295		
Inter-pair differences:					distance	rank
a-b	1.407	1.662	1.309	1.934	3.193	(3)
a-c	1.935	0.133	1.934	1.409	3.080	(2)
b-c	0.528	1.795	0.525	0.525	2.013	(1)

Sub-samples: a -- 1:50,000 scale, small triangles;
b -- 1:250,000 scale, large triangles;
c -- 1:50,000 scale, large triangles.

Because only two areas were investigated, no strong conclusions can be made regarding the results and the difference between the areas. The writer proposes the following as a possible explanation for the results obtained. First of all, the reduction in the number of triangles was more drastic for sample 18 than for sample 11 -- sub-samples 11b and 11c had about one third the number of triangles as did 11a, while 18b and 18c had only about one sixth the number in 18a. Secondly, the topography of area 18 was more complex than area 11. This can be seen by a visual inspection of the maps in Appendix III, and is reflected in the fact that 52 per cent more triangles were used to characterize sample 18's topography in the basic triangular data-sets (see Table 6.1). It is proposed that for area 11, the topographic texture was sufficiently large that the larger triangles in sub-sample 11c were able to retain most of the "terrain information" present in sub-samples 11a and 11d. Differences between the map scales due to contour generalization and the larger contour interval thus predominate, making sub-sample 11b the one most distant from the others in its terrain parameters. For area 18, the finer topographic texture and larger triangles combined to make the influences of map scale relatively less important than that of the reduced number of triangles. These proposals should be tested by further investigations which are beyond the scope of the present study.

6.8: <u>Summary</u>

Empirical tests were used to estimate the digitization times required for triangular data-sets and for regular grids. It was estimated that 43.0 seconds per point are required for the former and 8.3 seconds per point for the latter. The average triangular data-set would require about 2.6 times as long to prepare as the 15 by 15 grids used for comparisons. Theoretical considerations indicate that the former data-sets would need some 3.1 times as much computer storage space as would the grids.

Errors in the estimates of local relief, mean slope, and hypsometric integral were discussed, and various estimates of the roughness factor were given. In every case, the triangular data-sets based on surface-specific points gave better results than the 15 by 15 grids. Triangular data-set errors for local relief and mean slope were significantly less than those of the grids, as determined using the t-statistic. For the hypsometric integral, the grids produced a higher average error but the difference was not significant at the 95 per cent level.

The hypothetical linear relationship between grid error and grid spacing was used to estimate the grid spacing required to equal the precision of the triangular data-set estimates of the three parameters. The digitization times and computer storage requirements of these theoretical grids were determined, and for all three parameters the triangular data-sets required less time and space than did the grids.

An investigation of the reproduceability of triangular data-sets and the influences of map scale and triangle size was conducted. The reproduceability was good; the relative importance of map scale and triangle size appears to be related to the complexity of the terrain. If the triangles are too large, the topography is smoothed and the effect of map scale becomes less important. Further work will be required to test and quantify this proposed relationship.

Chapter 7: Summary and Conclusions

General geomorphometry is to be preferred over a specific approach because it does not depend upon any single geomorphic process nor on the identification of specific types of landforms. It is therefore more applicable to arbitrarily-bounded terrain samples stored in an electronic computer.

After a brief discussion of map precision and notation, approaches to computer terrain storage were discussed. This subject was reviewed in terms of digitization (data gathering) methods, actual computer storage and retrieval techniques, and assumptions about the behavior of the land surface between data points. In surface-specific sampling, points are selected which have particular significance in the topographic form -- these include peaks, pits, and passes, and points along ridges and valleys. In the surface-random approach, the points are selected according to criteria independent of the surface; usually either the locations of the points are determined by some type of grid, or the elevations of the points to be recorded are defined (contour sampling). Completely random sampling does not appear to produce as good a representation of a surface as does the stratified random approach represented by a grid. Generally, grids require much less computer storage allocation, since only one co-ordinate (the elevation) must be stored for each point. Digitized contour points require two co-ordinates, while for surface-specific points all three must be specified. In addition, the neighbours of a grid point are implicit in its position within the computer array, while these must be explicitly indicated for surface-specific points, requiring still more computer space. An arbitrary assumption about the behavior of the land surface between points is usually made; in the absence of evidence to the contrary, the linear assumption is generally the most reasonable. In the present study, the surface-specific point and regular grid approaches to computer terrain storage were compared with reference to the problem of estimating some selected geomorphometric parameters.

A large number of landform measures were reviewed, and were found to belong to a number of basic groups. These were texture and grain, relief, slope, dispersion of slope magnitude and orientation, and hypsometry. It was decided to select one parameter from each of these classes, but none of the grain and texture measures were readily adaptable to the computer methods used. Texture and grain were implicit in the sample area size and the density of sample points. The four parameters examined explicitly were local relief (H), mean slope ($\tan\alpha$), roughness factor ($\mathbb{R}$), and hypsometric integral ($\mathbb{HI}$).

In order to select some areas for detailed analysis and to provide data for assessing the theoretical errors in the estimates of some parameters, forty-two 7 by 7 km squares were selected from 1:50,000 scale maps of southern British Columbia using a stratified random sampling design. For each of these areas, local relief, hypsometric integral, mean slope, drainage density, stream source density, and peak density were estimated using manual methods. Relationships among these variables and their estimates were examined during correlation analysis. Relief, hypsometric integral, and peak density were used to divide the forty-two samples into fifteen "terrain types". A stratified random sample of six areas was derived from these to provide a basis for the comparison of the computer methods, and the geomorphology of each of the six areas was briefly described.

Theoretical errors involved in estimating the four selected parameters both from the triangular networks based upon surface-specific points and from regular grids were discussed, as were the actual analysis procedures employed. For local relief and the hypsometric integral at least, the precision of the grid estimates should be linearly related to the grid spacing; this probably holds true for the other measures also. The possibility of estimating other parameters, the relationships among the selected variables and between the numbers of points and triangles, and the theoretical computer storage requirements of the methods were also reviewed.

Finally, the results of the analysis of the topography of the six samples using the two approaches were reported. Sample 11 was used to investigate the reproduceability of the surface-specific sampling, and this and sample 18 used to study the effects of the numbers of points and the scale of the maps used. It was found that the relative importance of map scale and triangle size appears to depend upon the topographic texture. For coarse texture, map scale is more important, while for finer texture, the size of triangles used becomes dominant. This hypothesis should be tested by further research.

The triangular data-sets were found to produce better estimates of the parameters than the regular grids, even though the latter averaged more than twice as many points. The average surface-specific point data-set required some 2.6 times as much digitization time and 3.1 times as much computer storage space as did the 15 by 15 grids. The theoretical linear relationship between grid error and grid spacing was used to estimate the grid density required to equal the precision of the triangular data-sets. These hypothetical grids would require much more time and storage space than would the data-sets based on surface-specific points (see Table 6.6).

In conclusion, it appears that superior estimates of geomorphometric parameters can be obtained from triangular data-sets based on surface-specific points. Grids which would produce a comparable level of precision would theoretically require more digitization time and computer storage space. For a reasonably experienced terrain analyst, the triangular data-sets appeared to show good reproduceability; further investigation will be required to determine whether comparable results can be obtained using workers with less training and background. Such workers should be able to produce good results using grid sampling, since this approach lacks the subjective element involved in the selection of the surface-specific points.

References

Abrahams, A.D., 1972, Drainage densities and sediment yields in eastern Australia. Australian Geogr. Studies, v. 10, p. 19-41.

Ahnert, F., 1970, Functional relationships between denudation, relief, and uplift in large mid-latitude drainage basins. Am. J. Sci., v. 268, p. 243-263.

__________, 1972, Relief and denudation -- theoretical test of an empirical correlation. Internat. Geog. Congress, 1972, Event Ca6, Vancouver, B.C.

Akin, J.E., 1971, Calculations of mean areal depth of precipitation. J. Hydrol., v. 12, p. 363-376.

Bassett, K, and Chorley, R.J., 1971, An experiment in terrain filtering. Area, v. 3, p. 78-91.

Batchelder, R.B., 1950, Application of two relative relief techniques to an area of diverse landforms: A comparative analysis. Surv. & Mapping, v. 10, p. 110-118.

Boehm, B.W., 1967, Tabular representation of multivariate functions with application to topographic modeling. Assoc. for Computing Machinery, 22nd Nat. Conf., Proc., 1967, p. 403-415.

Boesch, H., and Kishimoto, H., 1966, Accuracy of cartometric data. Geographisches Institut der Universität Zurich, 1966, Contract No. DA-91-591-EUC-3262, Final Tech. Rept.

Calef, W.C., and Newcomb, R., 1953, An average slope map of Illinois. Annals Assoc. Am. Geog., v. 43, p. 305-316.

Carlston, C.W., 1963, Drainage density and streamflow. U.S. Geol. Surv., Prof. Paper 422-C, 8 pp.

Carson, M.A., & Kirkby, M.J., 1972, Hillslope form and process. Cambridge University Press, London, MacMillan, Toronto, 1972, 475 pp.

Cayley, A., 1859, On contour and slope lines. Phil. Mag., s. 4, v. 18, p. 264.

Chapman, C.A., 1952, A new quantitative method of topographic analysis. Am. J. Sci., v. 250, p. 428-452.

Chen, S.P., 1947, The relative relief of Tsuny, Kweichow. Journal, Geog. Soc. China, v. 14, p. 5.

Chorley, R.J., 1957, Climate and morphometry. J. Geol., v. 65, p. 628-638.

__________, 1958, Aspects of the morphometry of a 'poly-cyclic' drainage basin. Geog. J., v. 124, p. 370-374.

———, 1969, The drainage basin as the fundamental geomorphic unit. in Chorley, R.J., ed., Water, Earth and Man, Methuen, London, p. 77-99.

———, 1972, Spatial Analysis in Geomorphology. Methuen & Co. Ltd., London, 393 pp.

———, Malm, D.E.C., and Pogorzelski, H.A., 1957, A new standard for measuring drainage basin shape. Am. J. Sci., v. 255, p. 138-141.

———, and Morgan, M.A., 1962, Comparison of morphometric features, Unaka Mountains, Tennessee and North Carolina and Dartmour, England. Geol. Soc. Am. Bull., v. 73, p. 17-34.

———, and Morley, L.S.D., 1959, A simplified approximation for the hypsometric integral. J. Geog., v. 67, p. 566-571.

Clarke, J.I., 1966, Morphometry from maps. in Dury, G.H., ed., Essays in Geomorphology, Heinemann, London, p. 235-274.

Conacher, A.J., 1968, The nine unit landsurface model in southeast Queensland: preliminary observations. Proc. Fifth New Zealand Geog. Conf., p. 159-162.

Connelly, D.S., 1968, The Coding and Storage of Terrain Height Data: An Introduction to Numerical Cartography. Unpub. MS thesis, Cornell U., Sept. 1968, 141 pp.

———, 1972, Geomorphology and information theory. in Chorley, R.J., ed., Spatial Analysis in Geomorphology, Methuen & Co. Ltd., London, p. 91-108.

Coulson, A., and Gross, P.W., 1967, Measurement of the physical characteristics of drainage basins. Canada Dept. Energy, Mines & Res., Inland Waters Branch, Tech. Bull. No. 5, 22 pp.

Curray, J.R., 1956, The analysis of two-dimensional orientation data. J. Geol., v. 64, p. 117-131.

Donahue, J.J., 1972, Drainage intensity in western New York. Annals Assoc. Am. Geog., v. 62, p. 23-36.

Dury, G.H., 1951, Quantitative measurements of the available relief and the depth of dissection. Geol. Mag., v. 88, p. 339-343.

Evans, I.S., 1972, General geomorphometry, derivatives of altitude, and descriptive statistics. in Chorley, R.J., ed., 1972, Spatial Analysis in Geomorphology, Methuen & Co. Ltd., London, 1972, p. 17-90.

Eyles, R.J., 1966, Stream representation on Malayan maps. J. Trop. Geog., v. 22, p. 1-9.

———, 1969, Depth of dissection of the West Malaysian landscape. J. Trop. Geog., v. 28, p. 23-32.

Fisher, R.A., 1953, Dispersion on a sphere. Royal Soc. London, Proc., v. A-217, p. 295-305.

Flint, R.F., 1971, Glacial and Quaternary Geology. John Wiley & Sons, Inc., New York, 892 pp.

Gassmann, F., and Gutersohn, H., 1947, Kotenstreuung und Relieffactor. Geogr. Helv., v. 2, p. 122-139.

Gerenchuk, K.I., Gorash, I.K., and Topchiyeu, A.G., 1970, A method for establishing some parameters of the morphologic structure of landscapes. Sov. Geogr., v. 11, p. 262-271.

Gerrard, A.J.W., and Robinson, D.A., 1971, Variability in slope measurements. A discussion of the effects of different recording intervals and micro-relief in slope studies. Trans. IBG, 54, p. 45-54.

Giusti, E.V., and Schneider, W.J., 1965, Comparison of drainage on topographic maps of the Piedmont Province. U.S. Geol. Surv., Prof. Paper 450-E, p. E118-E120.

Glock, W.S., 1932, Available relief as a factor of control in the profile of a landform. J. Geol., v. 40, p. 74-83.

Gregory, K.J., 1966a, The composition of the drainage net. in Slaymaker, H.O., ed., Morphometric Analysis of Maps, Brit. Geomorph. Res. Gp., Occ. Paper No. 4, p. 9-11.

__________, 1966b, Dry valleys and the composition of the drainage net. J. Hydrol., v. 4, p. 327-340.

Griffiths, T.M., 1964, A comparative study of terrain analysis techniques. U. Denver Dept. Geog. Publ., Tech. Paper 64-2.

Haan, C.T., and Johnson, H.P., 1966, Rapid determination of hypsometric curves. Geol. Soc. Am. Bull., v. 77, p. 123-126.

Hammond, E.H., 1964, Analysis of properties in land form geography: an application to broad-scale land form mapping. Annals Assoc. Am. Geog., v. 54, p. 11-19.

Hardy, R.L., 1971, Multiquadric equations of topography and other irregular surfaces. J. Geophys. Res., v. 76, p. 1905-1915.

__________, 1972, The analytical geometry of topographic surfaces. Proc. Am. Congr. of Surv. and Mapping, 32nd Ann. Meeting, Wash. D.C., 1972, p. 163-181.

Harris, S.A., 1969, The meaning of till fabrics. Can. Geogr., v. 13, p. 317-337.

Hayre, H.S., 1962, Surface roughness of the moon. Photogramm. Engineering, v. 28, p. 139-140.

———————, and Moore, R.K., 1961, Theoretical scattering coefficient for near vertical incidence from contour maps. J. Res., Nat. Bureau of Standards, 65D, p. 427-432.

Hesler, J.L., and Johnson, W.C., 1972, Quantitative discrimination among hummocky stagnation moraine, end moraine, and ground moraine (abstract). Geol. Soc. Am., Abst. with Prog., v. 4, p. 326.

Hobson, R.D., 1967, FORTRAN IV programs to determine surface roughness in topography for the CDC 3400 computer. Comp. Contrib. 14, State Geol. Surv., Univ. of Kansas, Lawrence, 28 pp.

———————, 1972, Surface roughness in topography: a quantitative approach. in Chorley, R.J., ed., Spatial analysis in Geomorphology, Methuen & Co. Ltd., London, 1972, p. 221-246.

Holland, S.S., 1964, Landforms of British Columbia -- a physiographic outline. B.C. Dept. Mines & Petrol. Res., Bull. 48.

Hormann, K., 1969, Geomorphologische Kartenanalyse mit Hilfe elektronischer Rechenanlagen. Z. Geomorph., v. 13, p. 75-98.

———————, 1971, Morphometrie der Erdoberfläche. Kiel, 1971, 179 pp.

Horton, R.E., 1945, Erosional development of streams and their drainage basins -- hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull., v. 56, p. 275-370.

Huggins, K.H., 1935, The Scottish Highlands: a regional study. Scott. Geogr. Mag., v. 51, p. 296-306.

Hutchinson, P., 1970, A contribution to the problem of spacing raingauges in rugged terrain. J. Hydrol., v. 12, p. 1-14.

Imamura, G., 1937, Past glaciers and the present topography of the Japanese Alps. Science Repts. of Tokyo, Bunrika Daiguku, C.7, 61 pp.

Institute of British Geographers, 1971, Slopes form and process . Institute of British Geographers, Special Publ., No. 3.

Johnson, D., 1933, Available relief and texture of topography: a discussion. J. Geol., v. 41, p. 293-305.

Junkins, J.L., and Jancaitis, J.R., 1971, Mathematical terrain analysis. Am. Congr. on Surv. & Mapping, 31st Ann. Meeting, Wash. D.C., 1971, p. 658-678.

Kaitanen, V., 1969, A geographical study of the morphogenesis of northern Lapland. Fennia, v. 99, p. 1-85.

King, C.A.M., 1966, A morphometric example of Factor analysis. in Slaymaker, H.O., ed., Morphometric analysis of maps, Brit. Geomorph. Res. Gp., Occ. Paper No. 4.

———————, 1969, Trend surface analysis of the Central Pennines erosion surfaces. Trans. Inst. Brit. Geogr., v. 47, p. 47-59.

Langbein, W.B., and others, 1947, Topographic characteristics of drainage basins. U.S. Geol. Surv., Water Supply Paper 968-C, p. 99-114.

Lebedev, V.G., 1961, Principles of geomorphic regionalization. Sov. Geogr., v. 2, p. 59-64.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial Processes in Geomorphology. Freeman, San Francisco.

Mackay, J.R., 1953, The alternative choice in isopleth interpolation. Prof. Geogr., v. 5, p. 2-4.

Maner, S.V., 1958, Factors affecting sediment delivery rates in the Red Hills physiographic area. Am. Geophys. Union, Trans., v. 39, p. 669-675.

Martonne, E. de, 1941, Hypsometrie et morphologie: détermination et interpretation des altitudes moyennes de la France et de ses grandes régions naturelles. Annales de Geographie, v. 50, p. 241-254.

Mather, R.M., 1972, Areal classification in geomorphology. in Chorley, R.J., ed., Spatial Analysis in Geomorphology, Methuen & Co. Ltd., p. 305-322.

Maxwell, J.C., 1870, On hills and dales. Phil. Mag., 4th ser., London, v. 40, No. 269, Dec. 1870, p. 421-427.

Maxwell, J.C., 1960, Quantitative geomorphology of the San Dimas experimental forest, California. Dept. Geol., Columbia U., ONR, Contract NONR 389-042, Tech. Rept. No. 19.

McCoy, R.M., 1971, Rapid measurement of drainage density. Geol. Soc. Am. Bull., v. 82, p. 757-762.

Melton, M.A., 1957, An analysis of the relations among elements of climate, surface properties, and geomorphology. Dept. Geol. Columbia U., ONR, Contract NONR 389-042, Tech. Rept. No. 11.

———————, 1958, Correlation structure of morphometric properties of drainage systems and their controlling agents. J. Geol., v. 66, p. 442-460.

———————, 1965, The geomorphic and paleoclimatic significance of alluvial deposits in Southern Arizona. J. Geol., v. 73, p. 1-38.

Merlin, P., 1965, A propos des méthodes de morphometrie. Acta Geographica (Paris), v. 56, p. 14-20.

Monkhouse, F.J., and Wilkinson, H.R., 1952, Maps and Diagrams: Their Compilation and Construction. Second edition, 1964, University Paperbacks, Methuen & Co. Ltd., London, 432 pp.

Monmonier, M.S., 1969, Trends in upland accordance in Pennsylvania's Ridge and Valley section. Penna. Acad. Sci., Proc., v. 42, p. 157-162.

———————, Pfaltz, J.L., and Rosenfeld, D.A., 1966, Surface area from contour maps. Photogramm. Eng., v. 32, p. 476-482.

Morisawa, M., 1957, Accuracy of determinations of stream lengths from topographic maps. Trans Am. Geophys. Union, v. 38, p. 86-88.

Newell, W.L., 1970, Factors influencing the grain of the topography along the Willoughby Arch in northern Vermont. Geogr. Annlr., v. 52A, p. 103-112.

Pannekoek, A.J., 1962, Generalization of coastlines and contours. Internat. Yearbook of Cartography, v. 2, p. 55-75.

———————, 1967, Generalized contour maps, summit level maps, and streamline surface maps as geomorphological tools. Z. Geomorph., v. 11, p. 169-182.

Park, C.M., Lee, Y.H., and Scheps, B., 1970, Slope measurement from contour maps. U. of Maryland Comp. Sci. Centre, Tech. Rept. 70-109, Mar. 1970, College Pk., Md.

———————, ———————, and ———————, 1971, Slope measurement from contour maps . Phogogramm. Eng., v. 37, p. 277-283.

Partsh, J., 1911, Schlesien, eine Landeskunde für das deutsche Volk. II, S. 586, Breslau, 1911.

Péguy, C.P., 1942, Principes de morphometrie Alpine. Rev. de Geog. Alpine, v. 30, p. 453-486.

Peltier, L.C., 1962, Area sampling for terrain analysis. Prof. Geog., v. 14, p. 24-28.

Peucker, T.K., 1972, Computer cartography. Assoc. Am. Geog., Commission on College Geography, Resource Paper No. 17.

Pike, R.J., and Wilson, S.E., 1971, Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. Geol. Soc. Am. Bull., v. 82, p. 1079-1084.

Pillewizer, W., 1972, Talasymmetrie und Kartometrie. Z. Geomorph., v. 16, p. 449-462.

Piper, D.J.W., and Evans, I.S., 1967, Computer analysis of maps using a pencil follower. Geographical Articles, Cambridge , v. 9, p. 21-25.

Raisz, E., and Henry, J., 1937, An average slope map of southern New England. Geogr. Rev., v. 27, p. 467-472.

Roberts, M.C., and Klingeman, P.C., 1972, The relationship of drainage net fluctuation and discharge. International Geography 1972, W.P. Adams and F.M. Helleiner, eds., 22nd Internat. Geogr. Congress, Montreal.

Robinson, A.H., 1960, Elements of Cartography. 2nd edition. John Wiley & Sons, Inc., New York, 343 pp.

Rodda, J.C., 1970, A trend-surface analysis trial for the planation surfaces of north Cardiganshire. Trans. Inst.Brit. Geogr., v. 50, p. 107-114.

Ronca, L.B., and Green, R.R., 1970, Statistical geomorphology of the lunar surface. Geol. Soc. Am. Bull., v. 81, p. 337-352.

Rowan, L.C., McCauley, J.F., and Holm, E.A., 1971, Lunar terrain mapping and relative roughness analysis. U.S. Geol. Surv. Prof. Paper 599G., 32 pp.

Ruhe, R.V., 1950, Graphic analysis of drift topographies. Am. J. Sci., v. 248, p. 435-443.

——————, 1952, Topographic discontinuities of the Des Moines Lobe. Am. J. Sci., v. 250, p. 46-56.

Salisbury, N.E., 1962, Relief: slope relationships in glaciated terrain. Annals Assoc. Am. Geog., v. 52, p. 358-359.

Schumm, S.A., 1954, The relation of drainage basin relief to sediment loss. Pub. Internat. Assoc. Hydrol., IUGG, Tenth Gen. Assembly, Rome, 1954, v. 1, p. 216-219.

——————, 1956, Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol. Soc. Am. Bull., v. 67, p. 597-646.

——————, 1963, The disparity between present rates of denudation and orogeny. U.S. Geol. Surv. Prof. Paper 454-H, 13 pp.

Sharpnack, D.A., and Akin, G., 1969, An algorithm for computing slope and aspect from elevation. Photogramm. Engin., v. 35, Mar. 1969, p. 247-248.

Smith, G.-H., 1935, The relative relief of Ohio. Geogr. Rev., v. 25, p. 272-284.

——————, 1939, The Morphometry of Ohio: The average slope of the land (abst.). Annals Assoc. Am. Geog., v. 29, p. 94.

Smith, K.G., 1950, Standards of grading texture of erosional topography. Am. Sci., v. 248, p. 655-668.

Speight, J.G., 1968, Parametric description of landform . in Stewart, G.A., ed., Land Evaluation, Papers of CSIRO symp., in co-op. UNESCO, 26-31 Aug., 1968, p. 239-250.

———————, 1971, Log-normality of slope distribution. Z. Geomorph., v. 15, p. 290-311.

Spreen, W.C., 1947, A determination of the effect of topography upon precipitation. Trans., Am. Geophys. U., v. 28, p. 285-290.

Steinmetz, R., 1962, Analysis of vectorial data. J. Sed. Petrol., v. 32, p. 801-812.

Stone, R.O., and Dugundji, J., 1965, A study of microrelief -- its mapping, classification and quantification by means of a Fourier analysis. Engin. Geol., v. 1, p. 89-187.

Strahler, A.N., 1950, Equilibrium theory of erosional slopes approached by frequency distribution analysis. Am. J. Sci., v. 248, p. 673-696; 800-814.

———————, 1952, Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Am. Bull., v. 63, p. 1117-1142.

———————, 1956, Quantitative slope analysis. Geol. Soc. Am. Bull., v. 67, p. 571-596.

———————, 1957, Quantitative analysis of watershed geomorphology. Am. Geophys. U., Trans., v. 38, p. 913-920.

———————, 1958, Dimensional analysis applied to fluvially eroded landforms. Geol. Soc. Am. Bull., v. 69, p. 279-299.

Swan, S.B. St. C., 1967, Maps of two indices of terrain, Johor, Malaya. J. Trop. Geog., v. 25, p. 48-57.

Tanner, W.F., 1959, Examples of departure from the Gaussian in geomorphic analysis. Am. J. Sci., v. 257, p. 458-460.

———————, 1960, Numerical comparison of geomorphic samples. Science, v. 131, p. 1525-1526.

———————, 1962, Components of the hypsometric curve of the earth. J. Geophys. Res., v. 67, p. 2841-2843.

Tarrant, J.R., 1970, Comments on the use of trend-surface analysis in the study of erosion surfaces. Trans. Inst. Brit. Geogr., v. 51, p. 211-222.

Thomas, M.F., 1969, Geomorphology and land classification in tropical Africa. in Thomas, M.F., and Whittington, G.W., eds., Environment and land use in Africa . London, p. 103-145.

Thompson, M.M. , and Davey, C.H., 1953, Vertical accuracy of topographic maps. Surveying and Mapping, v. 13, p. 40-48.

Tipper, H.W., 1971, Glacial geomorphology and Pleistocene history of central British Columbia. Geol. Surv. Can., Bull. 196.

Tobler, W.R., 1969, Geographical filters and their inverses. Geographical Analysis, v. 1, p. 234-253.

————, and Davis, C.M., 1968, A digital terrain library. U. Mich., College of Lit., Science, and Arts, Dept. of Geog., Tech. Rept. ORA Proj. 08055, Ann Arbor, Mich.

Trewartha, G.T., and Smith, G.-H., 1941, Surface configuration of the Driftless Cuestaform Hill Land. Annals Assoc. Am. Geog., v. 31, p. 25-45.

Troeh, F.R., 1964, Landform parameters correlated to soil drainage. Soil Sci. Soc. Am. Proc., v. 28, p. 808-812.

————, 1965, Landform equations fitted to contour maps. Am. J. Sci., v. 263, p. 616-627.

Turner, A.K., and Miles, C.R., 1967, Terrain analysis by computer. Indiana Acad. Sci., Proc., v. 77, p. 256-270.

Van Lopik, J.R., and Kolb, C.R., 1959, A technique for preparing desert terrain analogs. U.S. Army Engin. Waterway Exp. Station, Vicksburg, Miss., Tech. Rept. 3-506.

Warntz, W., 1966, The topology of a socio-economic terrain and spatial flows. Papers, Regional Sci. Assoc., v. 17, p. 47-61.

————, 1968, A note on stream ordering and contour mapping. Harvard Papers in Theor. Geog., No. 18, Office of Naval Res., Tech. Rept., Proj. NR389-147.

Wentworth, C.K., 1930, A simplified method of determining the average slope of land surfaces. Am. J. Sci., v. 20, p. 184-194.

Williams, P.W., 1966, Suggested techniques for morphometric analysis of temperate karst landforms. in Slaymaker, H.O., ed., Morphometric Analysis of Maps, Brit. Geomorph. Res. Gp., Occ. Paper No. 4, p. 12-30.

Woldenberg, M.J., 1972, The average hexagon in spatial hierarchies . in Chorley, R.J., ed., Spatial Analysis in Geomorphology, Methuen, London, p. 322-352.

Wong, P.P., 1969. The surface configuration of Singapore Island: a quantitative description. J. Trop. Geog., v. 29, p. 64-74.

Wood, W.F., and Snell, J.B., 1957, The dispersion of geomorphic data around measures of central tendency and its application. Quartermaster Res. and Eng. Command, U.S. Army Study Rept. EA-8.

————, and ————, 1959, Predictive methods in topographic analysis I. Relief, Slope, and Dissection on inch-to-the mile maps in the United States. Quartermaster Res. and Eng. Command., U.S. Army, Tech. Rept. EP-112.

———————, and ———————, 1960, A quantitative system for classifying landforms. Quartermaster Res. and Eng. Command, U.S. Army, Tech. Rept. EP-124.

Young, A., 1972, Slopes. Oliver and Boyd, Edinburgh, 1972, 288 pp.

Zakrzewska, B., 1963, An analysis of landforms in a part of the central Great Plains. Annals Assoc. Am. Geog., v. 53, p. 536-568.

Appendix I: Notation

In this appendix, all variables and symbols used in the text are listed, together with their meanings or definitions. Exceptions are standard abbreviations (such as "M" for metres) which are not listed. For each entry, the text section where the sumbol first appeared is indicated in parentheses.

$a(h)$	the relative hypsometric function (3.6.1)
b	average distance between adjacent ridges and valleys (3.4.3)
c	a distance measure (2.5)
D	a density value (1.2)
D_d	drainage density (3.2.2)
D_p	peak density (3.2.4)
D_s	stream source density (3.2.3)
d	grid spacing (2.2)
E	elevation-relief ratio (3.6.2)
e_H	error in the grid estimate of local relief (5.1.2)
e_{HI}	relative error in the grid estimate of the hypsometric integral (5.4.2)
e_{max}	error in the grid estimate of the maximum elevation (5.1.2)
e_{min}	error in the grid estimate of the minimum elevation (5.1.2)
f	factor by which one wishes to improve grid accuracy (2.2)
G	grain of topography (3.2.1)
H	local relief (3.3.1)
H^*	grid estimate of local relief (4.3.3)
H_a	available relief (3.3.2)
H_d	drainage relief (3.3.3)
HI	the hypsometric integral (3.6.2)
HI^*	grid estimate of the hypsometric integral (4.3.5)
h	relative height (3.6.1)
$\bar{h}$	mean relative height (3.6.2)

I	the contour interval (3.4.1)
k	the vector dispersion factor (3.5)
L	total length of traverse lines used in line sampling estimates of slope (3.4.1) or drainage density (4.3.1)
$L(\%)$	vector strength in per cent (3.5)
N	number of objects or occurrences (1.2)
N_C	number of cells or triangles in network (5.6)
N_E	number of edges in network (5.6)
N_V	number of vertices or points in network (5.6)
P	length of drainage basin perimeter (3.2.2)
p	mean annual precipitation (4.3.6)
R	length of vector sum (3.5)
$\mathbb{R}$	roughness factor (3.5)
r	correlation coefficient (1.2)
S	size or wavelength of smallest features one wishes to detect (2.2)
s	a root-mean-square value (1.2)
s_d	root-mean-square distance (5.1.2)
s_e	root-mean-square error (1.1)
T	texture ratio (3.2.2)
t	year of map publication (4.3.6)
V	volume of landmass (3.2.4)
v	variability factor (3.5)
W	highest frequency present in a function (2.2)
x, y	geographic location co-ordinates (1.2)
z	altitude above sea level (1.2)
$\bar{z}$	mean elevation (3.6.2)
z_{max}	maximum elevation (3.6.1)

z^*_{max}	grid estimate of z_{max} (5.4.2)
z_{min}	minimum elevation (3.6.1)
z^*_{min}	grid estimate of z_{min} (5.4.2)
α	mean ground slope (3.4.1)
β	exponent in the general interpolation formula (2.5)
γ	slope near the maximum or minimum point (5.1.2)
δ	land slope at a point (1.1)
θ	angle of intersection between a traverse line and a contour or stream (3.4.1)
κ	precision parameter for Fisher's spherical probability distribution (3.5)

Appendix II: Topographic and Related Variables for 42 Areas in Southern British Columbia

In the following Table, the values for twelve terrain and related variables from the forty-two 7 by 7 km topographic samples examined in Chapter 4 are given. The parameters were listed in Table 4.3, and are also included in Appendix I. The six areas analyzed in detail in Chapter 6 are indicated by the symbol "#", while the highest and lowest value for each parameter are marked with the symbols "+" and "-", respectively. The mean and standard deviation for each variable, and the units of measurement, are indicated at the bottom of the Table.

All of the values reported in this Table are based on the exclusion of water surfaces from the calculations. If these were included, mean slope would be reduced for those areas including lakes or the ocean, and the values of some of the other parameters would also be influenced.

Area	D_d	N/L	D_s	D_p	H	H*	tan α	H	H*	$\bar{z}$	p	t
1	0.388	0.296	0.102	0.163	1247	884	0.167	0.602	0.540	1650	40	64
2	0.661	0.418	0.388	0.408	963	643	0.405	0.568	0.552	1818	40	61
3	0.292	0.184	0.041	0.694	329	235	0.091	0.343	0.481	951	15	31-
4	0.639	0.368	0.055	0.417	1268	1113	0.462	0.240-	0.259	1965	45	62
5	0.840	0.562	0.224	0.653	835	728	0.169	0.299	0.343	1046	16	62
6	0.482	0.286	0.000-	0.184	939	820	0.241	0.364	0.339	1113	20	58
7	0.776	0.459	0.224	0.122	1694	1636	0.445	0.352	0.361	1143	55	60
8#	0.555	0.347	0.102	0.102	1880	1655	0.609	0.428	0.479	1683	80	61
9	0.586	0.388	0.163	0.326	1387	1159	0.527	0.405	0.451	2077+	30	59
10	0.508	0.306	0.167	0.333	1740	1423	0.504	0.377	0.458	1967	70	66
11#	0.549	0.347	0.122	0.143	1709	1590	0.395	0.265	0.284	1148	30	65
12	0.476	0.317	0.102	0.408	1405	1207	0.460	0.512	0.434	1786	40	60
13	0.714	0.510	0.250	0.333	375	287	0.110	0.242	0.233	91-	40	51
14	1.231	0.837	1.089	0.122	1012	938	0.381	0.494	0.526	661	100	38
15	0.937	0.581	0.583	0.250	1326	1201	0.594	0.417	0.445	554	140	39
16	1.510	1.020	1.510+	0.306	1015	991	0.403	0.539	0.533	546	130	47
17	0.492	0.337	0.265	0.796	1408	1143	0.694+	0.529	0.562	1169	120	62
18#	1.847	1.163	1.429	0.286	883	619	0.395	0.546	0.429	1534	50	57
19	0.676	0.378	0.163	0.163	1905	1814	0.496	0.513	0.513	1129	18	58
20	0.684	0.459	0.061	0.408	1945	1610	0.601	0.314	0.380	754	130	65
21	0.563	0.357	0.250	0.568	686	567	0.299	0.251	0.272	172	70	49
22	1.322	0.837	0.821	0.359	1175	1128	0.376	0.286	0.297	426	120	34
23	0.720	0.398	0.291	0.521	920	832	0.342	0.371	0.365	341	90	60
24#	0.631	0.459	0.191	0.383	203-	174-	0.064	0.281	0.270	967	16	58
25	0.043-	0.031-	0.000-	0.041-	366	262	0.042	0.309	0.233	1021	14	65
26	0.408	0.235	0.020	0.306	773	585	0.262	0.343	0.450	635	20	61
27	0.478	0.286	0.163	0.184	287	214	0.056	0.494	0.607+	968	16	65
28	0.724	0.439	0.184	0.367	274	183	0.042-	0.540	0.492	831	12-	55
29	0.637	0.368	0.102	0.531	296	269	0.060	0.243	0.227-	1201	15	60
30	0.819	0.480	0.653	0.224	2122	1972+	0.607	0.562	0.601	1220	60	61
31#	0.290	0.255	0.106	0.553	1195	1054	0.225	0.348	0.392	1480	23	68+
32	0.657	0.459	0.104	0.521	338	329	0.101	0.562	0.559	1141	15	67
33	0.326	0.194	0.041	0.204	272	192	0.043	0.272	0.302	799	17	60
34	0.735	0.500	0.490	0.429	854	707	0.257	0.409	0.485	1187	47	60
35	2.051+	1.316+	1.408	0.306	613	471	0.256	0.268	0.344	176	105	36
36	0.657	0.418	0.125	0.271	738	643	0.157	0.252	0.280	186	90	61
37	1.420	1.023	0.256	0.977+	716	550	0.393	0.334	0.382	239	125	61
38	0.531	0.357	0.267	0.511	655	559	0.373	0.322	0.374	211	70	64
39	0.496	0.306	0.167	0.479	1012	860	0.582	0.386	0.430	400	70	64
40	0.661	0.398	0.286	0.286	495	464	0.200	0.347	0.349	182	70	64
41#	0.882	0.531	0.673	0.490	869	752	0.400	0.403	0.371	380	100	61
42	0.569	0.316	0.467	0.422	968	741	0.519	0.434	0.456	420	160+	61
mean	0.725	0.465	0.360	0.370	978	838	0.329	0.390	0.408	937	60	58
s	0.401	0.265	0.413	0.195	526	488	0.189	0.109	0.107	566	42	9
units	km^{-1}	km^{-1}	km^{-2}	km^{-2}	m	m				m	inches	yr

Appendix IIIa: Computer Program

In this appendix, the FORTRAN IV program listing for the computer program used in this study (program GEOTRI) is given. Requirements for the input data are contained in comments at the beginning of the program listing.

```
C*****************************************************************************
C
C      PROGRAM: GEOTRI
C      PURPOSE: TO DETERMINE SELECTED GEOMORPHOMETRIC PARAMETERS BY
C            ANALYSIS OF TRIANGULAR FACETS WHICH APPROXIMATE THE SURFACE,
C            POSSIBLY BASED ON GRID DATA
C      WRITTEN: DAVID M. MARK, GEOGRAPHY, U.B.C., 1973
C
C      INPUT: EACH JOB REQUIRES A JOB CARD AND A TITLE CARD, FOLLOWED BY
C                THE DATA IF REQUIRED FOR THE JOB.
C            JOB CARD: COL 3-5  ITYPE=0: PRE-TRIANGULATED DATA.
C                                    =1: GRID DATA
C                                    =999: END OF RUN (FOLLOWS LAST JOB)
C                            10  NEWP=0: READ NEW DATA POINTS
C                                   =1: USE SAME POINTS AS PREVIOUS JOB
C                            15  NEWT=0: READ OR COMPUTE NEW TRIANGLES
C                                   =1: USE SAME TRIANGLES AS PREVIOUS JOB
C                         16-27  XSCALE: NUMBER OF METRES IN ONE UNIT IN
C                                       X-DIRECTION, OR COLUMN SPACING FOR
C                                       GRID DATA. DEFAULTS TO 1.0 IF NOT
C                                       SPECIFIED. FORMAT: F12.5
C                         28-39  YSCALE: AS ABOVE, FOR Y-DIRECTION OR
C                                       ROW SPACING, DEFAULTS TO XSCALE.
C                         40-51  ZSCALE: NUMBER OF METRES IN ONE UNIT IN
C                                       Z-DIRECTION. DEFAULTS TO 1.0
C                            56  LAKE=0: ANALYZE ALL TRIANGLES.
C                                   =1: EXCLUDE LAKE AND OCEAN TRIANGLES.
C                            61  ITRI=0: OMIT TRIANGLE LIST.
C                                   =1: LIST PARAMETERS FOR EACH TRIANGLE.
C                            66  IDIAG=0: USE NW-SE DIAGONALS TO PRODUCE
C                                        TRIANGLES FROM GRID.
C                                    =1: USE NE-SW DIAGONALS.
C                         67-71  NR: NUMBER OF ROWS IN MATRIX,
C                         72-76  NC: NUMBER OF COLUMNS IN MATRIX
C
C            TITLE CARD: TITLE, MAXIMUM OF 76 CHARACTERS, IF NO TITLE IS
C                DESIRED, A BLANK CARD MUST BE INSERTED.
C
C            DATA:
C                PRE-TRIANGULATED DATA (ITYPE=0):
C                 -DATA POINTS, IF REQUIRED, EACH CARD HAVING POINT
C                  NUMBER AND X, Y, AND Z-CO-ORDINATES.(FORMAT AS WRITTEN
C                  IS I5,3F6.0)
C                 -LAST DATA POINT MUST BE FOLLOWED BY A BLANK CARD
C                 -TRIANGLES, IF REQUIRED, EACH CARD HAVING TRIANGLE
C                  NUMBER, POINT NUMBERS OF THREE VERTICES, AND "L",
C                  WHICH EQUALS 1 IF THE TRIANGLE IS ON A LAKE OR THE
C                  OCEAN, ZERO OTHERWISE. (FORMAT AS WRITTEN, 5I5)
C                 -LAST TRIANGLE MUST BE FOLLOWED BY A BLANK CARD
C                GRID DATA (ITYPE=1):
C                 -EACH ROW ON A SEPARATE CARD. (FORMAT AS WRITTEN: 3X,
C                  15F5.0). NO BLANK CARD IS INCLUDED, SINCE NUMBER OF
C                  ROWS (NR) IS SPECIFIED ON THE JOB CARD.
C
C            AS NOTED ABOVE, LAST JOB IS FOLLOWED BY A CARD WITH "999" IN
C                COLUMNS 3-5 TO END THE RUN.
C
C      RESTRICTIONS: AS WRITTEN, THERE ARE THE FOLLOWING RESTRICTIONS:
```

```
C              -MAXIMUM NUMBER OF POINTS (NP) IS 500;
C              -MAXIMUM NUMBER OF TRIANGLES (NT) IS 1000;
C              -MATRIX MAY NOT HAVE MORE THAN 20 ROWS (NR) OR 15 COLUMNS
C               (NC);
C              -IF DIMENSIONS ARE INCREASED, KEEP IN MIND THAT:
C                   -(NR-1)*(NC-1) CANNOT EXCEED NP;
C                   - NT SHOULD BE DIMENSION TO 2*NP.
C
C*****************************************************************************
C
      DIMENSION X(500),Y(500),Z(500),IT(1000),IV(1000),JV(1000),KV(1000)
     1,LV(1000),TITLE(19),SUM(12)
      COMMON X,Y,Z,IT,IV,JV,KV,LV,TITLE,NP,NT,LAKE,ITRI
      RAD=0.017453293
      JOBS=0
   99 CALL READER
      IF(LAKE.EQ.999) GO TO 999
      ALAKE=0.
      NL=0
      ZMAX=-99999.
      ZMIN=99999.
      IZMAX=0
      IZMIN=0
      DO 3 I=1,12
      SUM(I)=0.
    3 CONTINUE
      IF(ITRI.EQ.0) GO TO 94
      WRITE(6,152) (TITLE(II),II=1,19)
  152 FORMAT('1',19A4,//)
      WRITE(6,500)
  500 FORMAT('  NO.        CORNERS          L         ZM',10X,'MAP AREA        TRUE
     1 AREA        SLOPE',/)
   94 DO 6 I=1,NT
      IF(Z(IV(I)).LE.ZMAX) GO TO 60
      ZMAX=Z(IV(I))
      IZMAX=IV(I)
   60 IF(Z(JV(I)).LE.ZMAX) GO TO 61
      ZMAX=Z(JV(I))
      IZMAX=JV(I)
   61 IF(Z(KV(I)).LE.ZMAX) GO TO 62
      ZMAX=Z(KV(I))
      IZMAX=KV(I)
   62 IF(Z(IV(I)).GE.ZMIN) GO TO 63
      ZMIN=Z(IV(I))
      IZMIN=IV(I)
   63 IF(Z(JV(I)).GE.ZMIN) GO TO 64
      ZMIN=Z(JV(I))
      IZMIN=JV(I)
   64 IF(Z(KV(I)).GE.ZMIN) GO TO 65
      ZMIN=Z(KV(I))
      IZMIN=KV(I)
   65 CONTINUE
      VEC11=X(JV(I))-X(IV(I))
      VEC12=Y(JV(I))-Y(IV(I))
      VEC13=Z(JV(I))-Z(IV(I))
      VEC21=X(KV(I))-X(IV(I))
      VEC22=Y(KV(I))-Y(IV(I))
      VEC23=Z(KV(I))-Z(IV(I))
```

```
            C       VEC1 AND VEC2 ARE VECTORS ALONG 2 SIDES OF THE TRIANGLE
0047                ZM=(Z(IV(I))+Z(JV(I))+Z(KV(I)))/3.
            C       ZM IS THE MEAN ELEVATION OF THE TRIANGLE
0048                V1=VEC12*VEC23-VEC13*VEC22
0049                V2=VEC13*VEC21-VEC11*VEC23
0050                V3=VEC11*VEC22-VEC12*VEC21
            C       V IS THE CROSS PRODUCT OF VEC1 AND VEC2, AND IS THE ORTHOGONAL TO
            C       THE TRIANGLE
0051                IF(V3.GE.0.0) GO TO 4
0052                V1=(-1.)*V1
0053                V2=(-1.)*V2
0054                V3=(-1.)*V3
0055              4 CONTINUE
            C       THIS MAKES THE VECTOR POINT "UP"
0056                VL=SQRT(V1*V1+V2*V2+V3*V3)
0057                AT=VL/2.
            C       THE LENGTH OF V IS TWICE THE TRUE AREA OF THE TRIANGLE, AT
0058                U1=V1/VL
0059                U2=V2/VL
0060                U3=V3/VL
0061                A=V3/2.
            C       THE "MAP" OR PROJECTED AREA IS HALF THE Z-COMPONENT OF V
0062                DIP=1.5707963-ARSIN(U3)
0063                S=TAN(DIP)
            C       S IS THE SLOPE TANGENT
            C       NOTE: IF OTHER CHARACTERISTICS OF INDIVIDUAL TRIANGLES ARE DESIRED
            C             THE APPROPRIATE STATEMENTS SHOULD BE INSERTED HERE AND THE
            C             WRITE STATEMENT CHANGED.  EG.: ORIENTATION OF TRIANGLE.
0064                IF(ITRI.EQ.0) GO TO 90
0065                WRITE(6,200) IT(I),IV(I),JV(I),KV(I),LV(I),ZM,A,AT,S
0066            200 FORMAT(5I5,4E15.8)
0067             90 CONTINUE
0068                IF(LV(I).NE.1) GO TO 7
0069                ALAKE=ALAKE+A
0070                NL=NL+1
            C       ALAKE IS THE TOTAL AREA OF LAKES + OCEAN; NL IS THE NUMBER OF
            C       TRIANGLES FALLING ON WATER
0071                IF(LAKE.EQ.0) GO TO 7
0072                IF(ITRI.NE.0) WRITE(6,300) IT
0073            300 FORMAT(' TRIANGLE # ',I3,' IS ON A LAKE OR THE OCEAN AND IS EXCLUD
               1ED')
0074                GO TO 6
0075              7 SUM(1)=SUM(1)+A
0076                SUM(2)=SUM(2)+AT
0077                SUM(3)=SUM(3)+ZM*A
0078                SUM(4)=SUM(4)+S
0079                SUM(5)=SUM(5)+S*A
0080                SUM(6)=SUM(6)+S*AT
0081                SUM(7)=SUM(7)+U1
0082                SUM(8)=SUM(8)+U2
0083                SUM(9)=SUM(9)+U3
0084                SUM(10)=SUM(10)+V1/2.
0085                SUM(11)=SUM(11)+V2/2.
0086                SUM(12)=SUM(12)+V3/2.
0087              6 CONTINUE
            C
            C       THE FOLLOWING SECTION COMPUTES GEOMORPHOMETRIC PARAMETERS
            C
```

```
          IF(LAKE) 18,19,18
       18 ATOT=SUM(1)+ALAKE
          NTA=NT-NL
          GO TO 20
       19 ATOT=SUM(1)
          NTA=NT
       20 CONTINUE
C         ATOT IS THE TOTAL AREA, WHILE SUM(1) IS THE ANALYSIS AREA, WHICH
C         MAY EXCLUDE LAKES,
C         NT IS THE TOTAL NUMBER OF TRIANGLES, NTA THE NUMBER FOR ALALYSIS
          PLAKE=100.*ALAKE/ATOT
        9 CONTINUE
          TN=FLOAT(NTA)
          ZM=SUM(3)/SUM(1)
          SM1=SUM(4)/TN
          SM2=SUM(5)/SUM(1)
          SM3=SUM(6)/SUM(2)
C         THE SM'S ARE MEAN SLOPES: SM1..UNWEIGHTED; SM2..WTD BY A; SM3..BY
          H=ZMAX-ZMIN                                                    AT.
          HYPS=(ZM-ZMIN)/H
C         HYPS IS THE HYPSOMETRIC INTEGRAL
          ARATIO=SUM(2)/SUM(1)
          AMTRI=SUM(1)/TN
C         AMTRI IS THE MEAN AREA OF THE TRIANGLES ANALYZED
C
C         THIS SECTION IS FOR VECTORIAL ANALYSIS. VARIABLES RELATED TO UNIT
C         (UNWEIGHTED) VECTOR ANALYSIS INCLUDE "U" IN NAMES, THOSE RELATED
C         TO WEIGHTED ANALYSIS INCLUDE "V".
C         R=VECTOR LENGTH, K=PRECISION PARAMETER, KI=100/K,L=VECTOR STRENGTH
C         (%), RF=ROUGHNESS FACTOR, O=ORIENTATION, D=DIP OF MEAN VECTOR
C
          RU=SQRT(SUM(7)**2+SUM(8)**2+SUM(9)**2)
          RV=SQRT(SUM(10)**2+SUM(11)**2+SUM(12)**2)
          UK=(TN-1.)/(TN-RU)
          UKI=100./UK
          UL=100.*RU/TN
          VL=100.*RV/SUM(2)
          RFU=100.-UL
          RFV=100.-VL
C         UL: VECTOR STRENGTH, UNIT VECTORS; VL: WEIGHTED BY AT.
          AU=SUM(7)/RU
          BU=SUM(8)/RU
          CU=SUM(9)/RU
          AV=SUM(10)/RV
          BV=SUM(11)/RV
          CV=SUM(12)/RV
          IF(BU.NE.0.0) GO TO 10
          IF(AU)11,12,13
       11 OU=270.
          GO TO 24
       12 OU=0.0
          GO TO 24
       13 OU=90.
          GO TO 24
       10 CONTINUE
          OU=ATAN(AU/BU)/RAD
          IF(OU)23,25,25
       25 IF(BU)33,24,24
```

```
      23 IF(BU)33,32,32
      32 OU=180.+OU
      33 OU=OU+180.
      24 CONTINUE
         DU=ARSIN(CU)/RAD
         IF(BV.NE.0.0) GO TO 14
         IF(AV) 15,16,17
      15 OV=270.
         GO TO 44
      16 OV=0.0
         GO TO 44
      17 OV=90.
         GO TO 44
      14 CONTINUE
         OV=ATAN(AV/BV)/RAD
         IF(OV)43,45,45
      45 IF(BV)53,44,44
      43 IF(BV)53,52,52
      52 OV=OV+180.
      53 OV=OV+180.
      44 CONTINUE
         DV=ARSIN(CV)/RAD
C
C        THE FOLLOWING SECTION PRINTS OUT RESULTS
C
         WRITE(6,152) (TITLE(II),II=1,19)
         WRITE(6,600) NP,NT,ATOT,PLAKE,NTA,SUM(1),AMTRI
     600 FORMAT(' GENERAL:        ',//,'NUMBER OF POINTS    =',10X,I5,/,'NUMBER
        1 OF TRIANGLES=',10X,I5,/,'TOTAL AREA              =',E15.8,/,'PERCENT L
        2AKES + SEA=',8X,F7.2,/,'NUMBER FOR ANALYSIS=',10X,I5,/,'AREA FOR A
        3NALYSIS  =',E15.8,/,'MEAN TRIANGLE AREA =',E15.8,//)
         WRITE(6,601) ZMIN,IZMIN,ZMAX,IZMAX,H,HYPS,SM1,SM2,SM3,ARATIO
     601 FORMAT(' GEOMORPHOMETRY:',//,'MINIMUM ELEVATION        =',F8.2,'  LO
        9CATED AT POINT NUMBER',I4,/,'MAXIMUM ELEVATION        =',F8.2,'  LOC
        1ATED AT POINT NUMBER',I4,/,'LOCAL RELIEF              =',F8.2,10X,/,'
        2HYPSOMETRIC INTEGRAL    =',F8.5,/,'MEAN SLOPE:',/,'  UNWEIGHTED
        3           =',F8.5,/,'  WEIGHTED BY MAP AREA  =',F8.5,/,'  WEIGHTED B
        4Y TRUE AREA =',F8.5,/,'AREA RATIO                 =',F8.5,//)
         WRITE(6,602) OU,DU,UL,UK,UKI,RFU,OV,DV,VL,RFV
     602 FORMAT(' VECTOR ANALYSIS:',//,'UNWEIGHTED(UNIT VECTORS):',/,'  ORI
        1ENTATION      =',F8.2,/,'  DIP                    =',F8.2,/,'  L(%)
        2      =',F8.2,/,'  K                    =',F8.2,/,'  100/K            =',
        3F8.2,/,'  ROUGHNESS FACTOR=',F8.2,//,'WEIGHTED BY TRUE AREA:',/,'
        4 ORIENTATION      =',F8.2,/,'  DIP                    =',F8.2,/,'  L(%)
        5          =',F8.2,/,'  ROUGHNESS FACTOR=',F8.2)
         JOBS=JOBS+1
         GO TO 99
     999 WRITE(6,900) JOBS
     900 FORMAT('1','END OF RUN.  THIS RUN INCLUDED ',I3,' JOBS.')
         STOP
         END
```

TOTAL MEMORY REQUIREMENTS 0013A6 BYTES

COMPILE TIME =   1.0 SECONDS

```
           SUBROUTINE READER
           DIMENSION X(500),Y(500),Z(500),IT(1000),IV(1000),JV(1000),KV(1000)
          1,LV(1000),TITLE(19),ALT(20,20),IDM(20,20)
           COMMON X,Y,Z,IT,IV,JV,KV,LV,TITLE,NP,NT,LAKE,ITRI
           READ(5,100)ITYPE,NEWP,NEWT,XSCALE,YSCALE,ZSCALE,LAKE,ITRI,IDIAG,NR
          1,NC
  100      FORMAT(3I5,3E12.5,5I5)
           IF(ITYPE.NE.999) GO TO 1
           LAKE=999
           RETURN
    1      READ(5,103)(TITLE(I),I=1,19)
  103      FORMAT(19A4)
           IF(XSCALE.EQ.0.0) XSCALE=1.0
           IF(YSCALE.EQ.0.0) YSCALE=XSCALE
           IF(ZSCALE.EQ.0.0) ZSCALE=1.0
           IF(ITYPE.EQ.1) GO TO 50
           IF(NEWP.EQ.1) GO TO 3
           NP=0
    2      READ(5,101)I,X(I),Y(I),Z(I)
  101      FORMAT(I5,3F6.0)
           IF(I.EQ.0) GO TO 3
           X(I)=X(I)*XSCALE
           Y(I)=Y(I)*YSCALE
           Z(I)=Z(I)*ZSCALE
           NP=NP+1
           GO TO 2
    3      IF(NEWT.EQ.1) GO TO 55
           NT=1
    4      READ(5,102)IT(NT),IV(NT),JV(NT),KV(NT),LV(NT)
  102      FORMAT(5I5)
           IF(IT(NT).EQ.0) GO TO 5
           NT=NT+1
           GO TO 4
    5      NT=NT-1
   55      WRITE(6,200)(TITLE(I),I=1,19)
  200      FORMAT('1',19A4,/)
           WRITE(6,201) NP,NT
  201      FORMAT(' THIS DATA SET WAS TRIANGULATED MANUALLY; IT CONTAINS ',I3
          1,' POINTS AND ',I3,' TRIANGLES.',//'OPTIONS:')
           IF(NEWP.EQ.1) WRITE(6,202)
  202      FORMAT('  -USES SAME POINTS AS PRECEDING DATA SET')
           IF(NEWT.EQ.1) WRITE(6,203)
  203      FORMAT('  -USES SAME TRIANGLES AS PRECEDING DATA SET')
           IF(XSCALE.NE.1.0) WRITE(6,204) XSCALE
  204      FORMAT('   -XSCALE=',E12.5)
           IF(YSCALE.NE.1.0) WRITE(6,205) YSCALE
  205      FORMAT('   -YSCALE=',E12.5)
           IF(ZSCALE.NE.1.0) WRITE(6,206) ZSCALE
  206      FORMAT('   -ZSCALE=',E12.5)
           IF(LAK.EQ.1) WRITE(6,207)
  207      FORMAT('   -LAKES ARE EXCLUDED FROM THE ANALYSIS')
           RETURN
   50      IF(NEWP.EQ.1) GO TO 61
           DO 60 I=1,NR
   60      READ(5,150)(ALT(I,J),J=1,NC)
  150      FORMAT(3X,15F5.0)
           NP=NR*NC
           NR1=NR-1
```

```
              NC1=NC-1
              NT=2*NR1*NC1
              DO 51 I=1,NR
              DO 51 J=1,NC
              ID=(I-1)*NC+J
              IDM(I,J)=ID
              X(ID)=FLOAT(J-1)*XSCALE
              Y(ID)=FLOAT(NR-I)*YSCALE
              Z(ID)=ALT(I,J)*ZSCALE
      51      CONTINUE
      61      CONTINUE
              INT=1
              DO 52 I=1,NR1
              DO 52 J=1,NC1
              IF(IDIAG)53,53,54
      53      IT(INT)=INT
              IV(INT)=IDM(I,J)
              JV(INT)=IDM(I+1,J)
              KV(INT)=IDM(I+1,J+1)
              LV(INT)=0
              INT=INT+1
              IT(INT)=INT
              IV(INT)=IDM(I,J)
              JV(INT)=IDM(I,J+1)
              KV(INT)=IDM(I+1,J+1)
              LV(INT)=0
              INT=INT+1
              GO TO 52
      54      IT(INT)=INT
              IV(INT)=IDM(I,J)
              JV(INT)=IDM(I,J+1)
              KV(INT)=IDM(I+1,J)
              LV(INT)=0
              INT=INT+1
              IT(INT)=INT
              IV(INT)=IDM(I,J+1)
              JV(INT)=IDM(I+1,J)
              KV(INT)=IDM(I+1,J+1)
              LV(INT)=0
              INT=INT+1
      52      CONTINUE
              INT=INT-1
              WRITE(6,200)(TITLE(I),I=1,19)
              IF(INT.NE.NT) WRITE(6,300)INT,NT
     300      FORMAT(' INT=',I4,',BUT NT=',I4,/)
              WRITE(6,301) NR,NC,NP,NT
     301      FORMAT(' THIS DATA SET IS BASED ON A ',I3,' BY ',I3,' ALTITUDE MAT
             1RIX;',/,' IT CONTAINS ',I3,' POINTS AND ',I3,' TRIANGLES',//,'OPTI
             2ONS:')
              IF(NEWP.EQ.1) WRITE(6,202)
              IF(NEWT.EQ.1) WRITE(6,203)
              IF(XSCALE.EQ.YSCALE)WRITE(6,302) XSCALE
     302      FORMAT('  -SQUARE GRID, GRID SPACING=',E12.5,' METRES')
              IF(XSCALE.NE.YSCALE) WRITE(6,303) XSCALE,YSCALE
     303      FORMAT('  -COLUMN SPACING=',E12.5,' METRES; ROW SPACING=',E12.5,'
             1METRES')
              IF(IDIAG.EQ.0) WRITE(6,304)
     304      FORMAT('  -USED NORTHWEST-SOUTHEAST DIAGONALS')
```

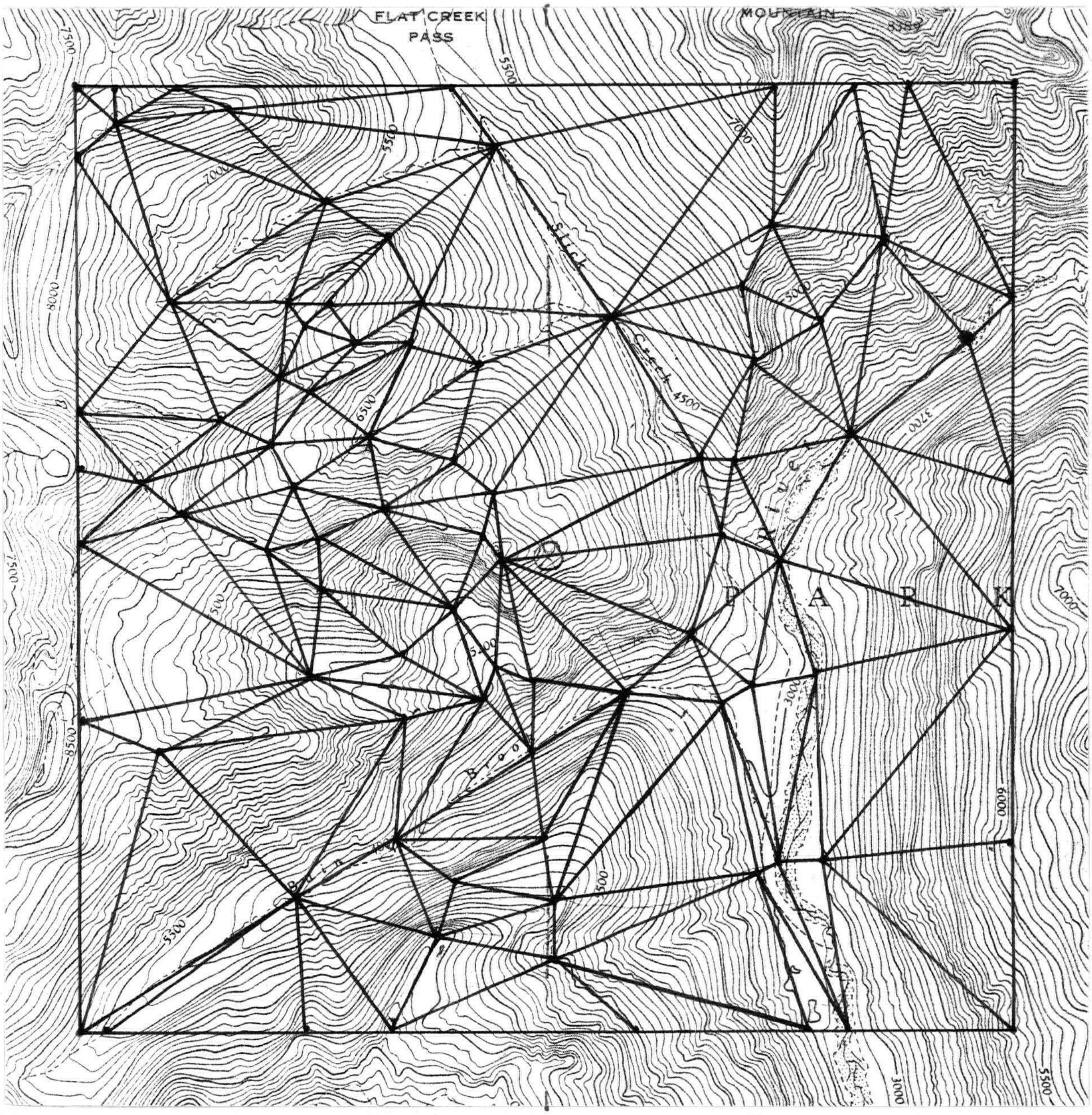
```
0111            IF(IDIAG.EQ.1) WRITE(6,305)
0112      305   FORMAT('  -USED NORTHEAST-SOUTHWEST DIAGONALS')
0113            IF(ZSCALE.NE.1.0) WRITE(6,206) ZSCALE
0114            RETURN
0115            END
```

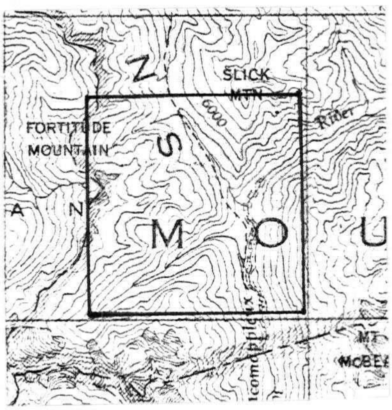
TOTAL MEMORY REQUIREMENTS 00182C BYTES

COMPILE TIME =   0.5 SECONDS

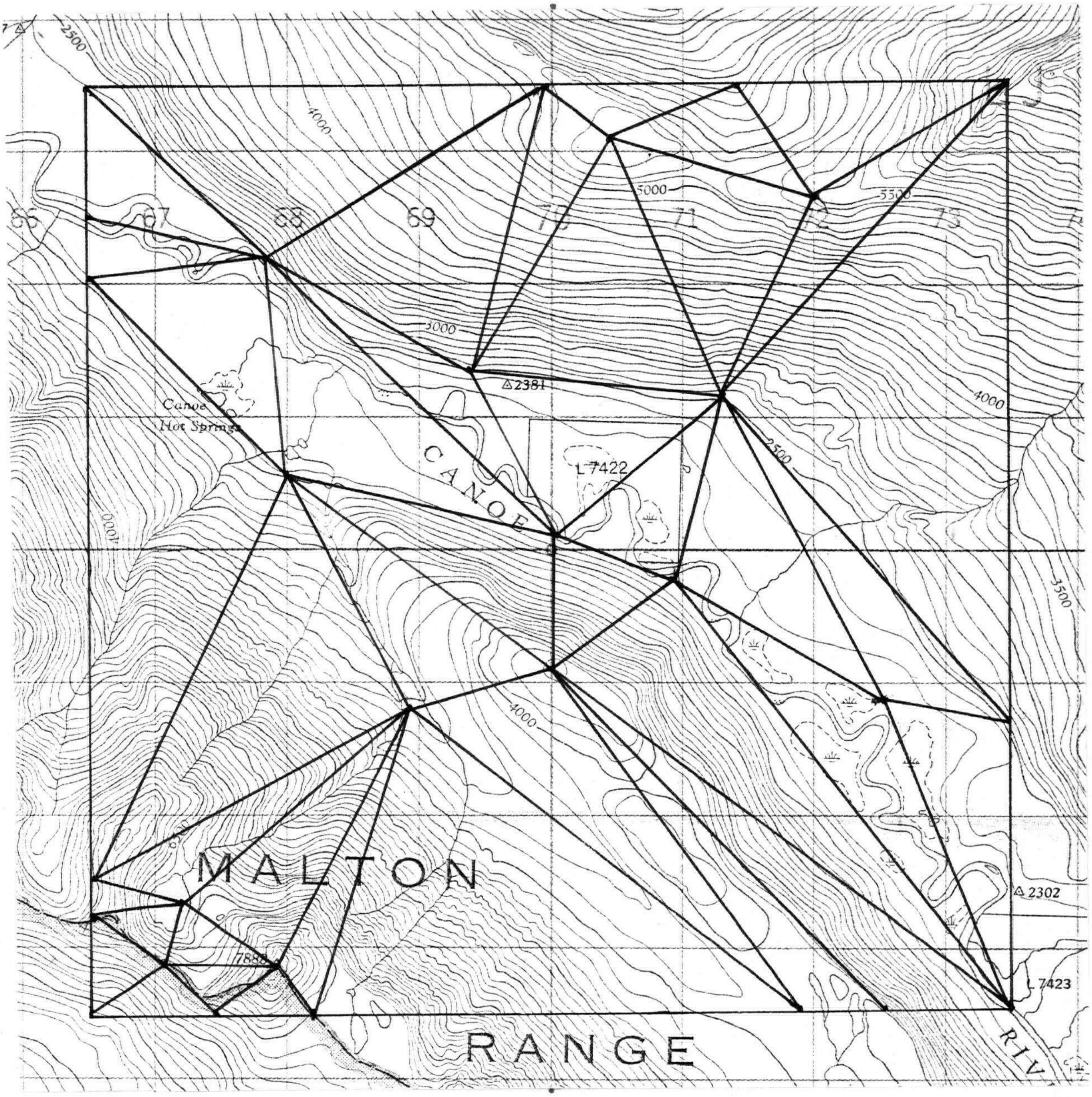
Appendix IIIb: Triangular Data-sets

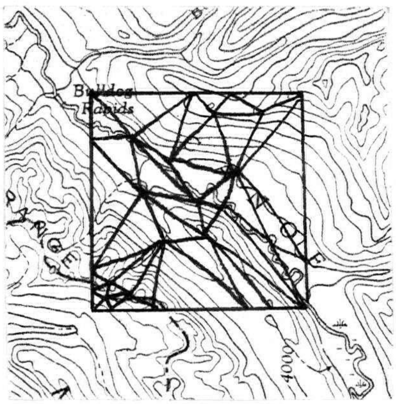
Maps of all the triangular data-sets analyzed in this study are given, with the exception of sample 11a which was illustrated in Figure 6.1. These maps are all at the scale of 1:50,000; 1:250,000 scale maps of the same areas are given in insets.



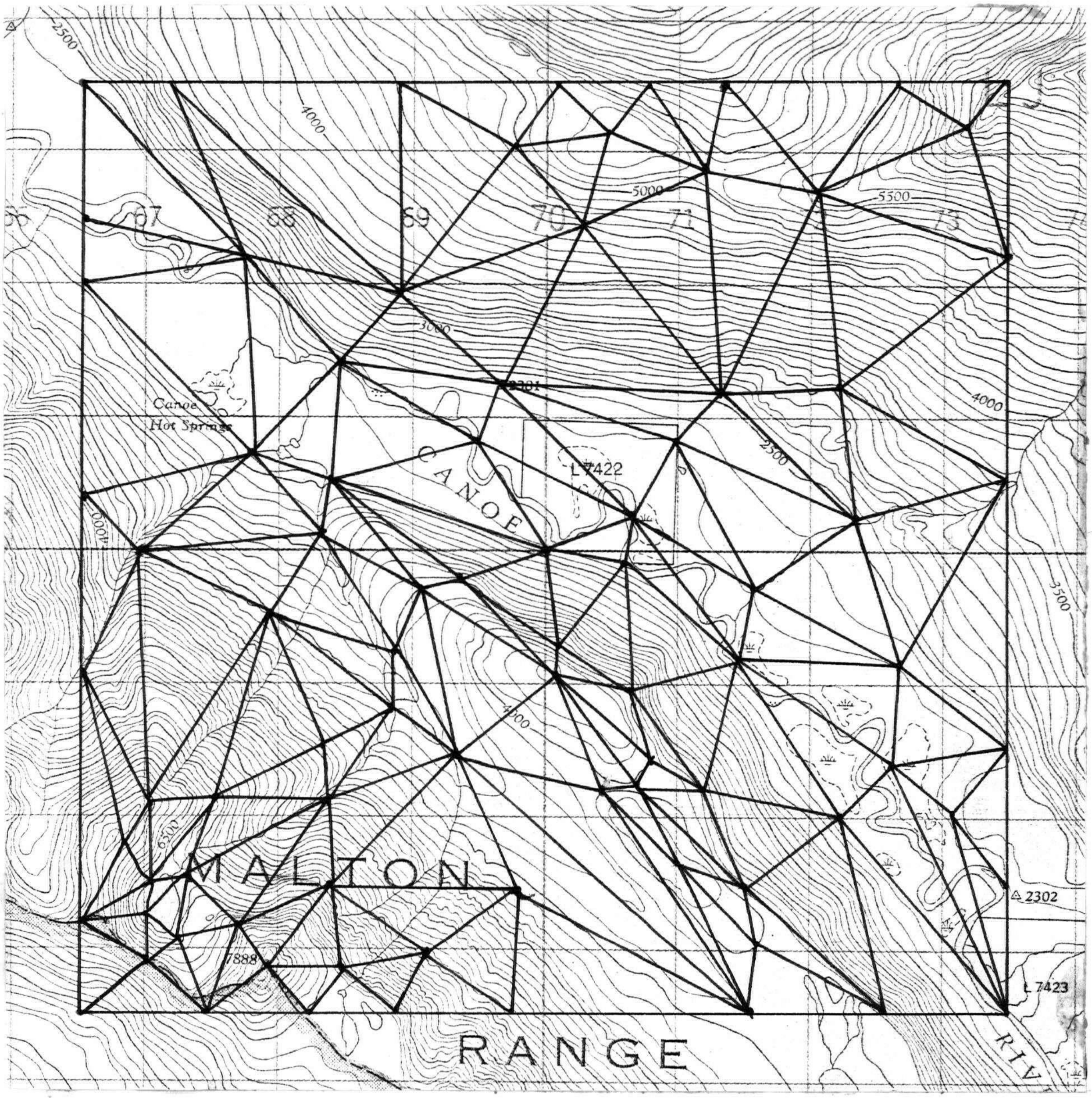


Sample 8, Illecillewaet map-area (82 N/4E)

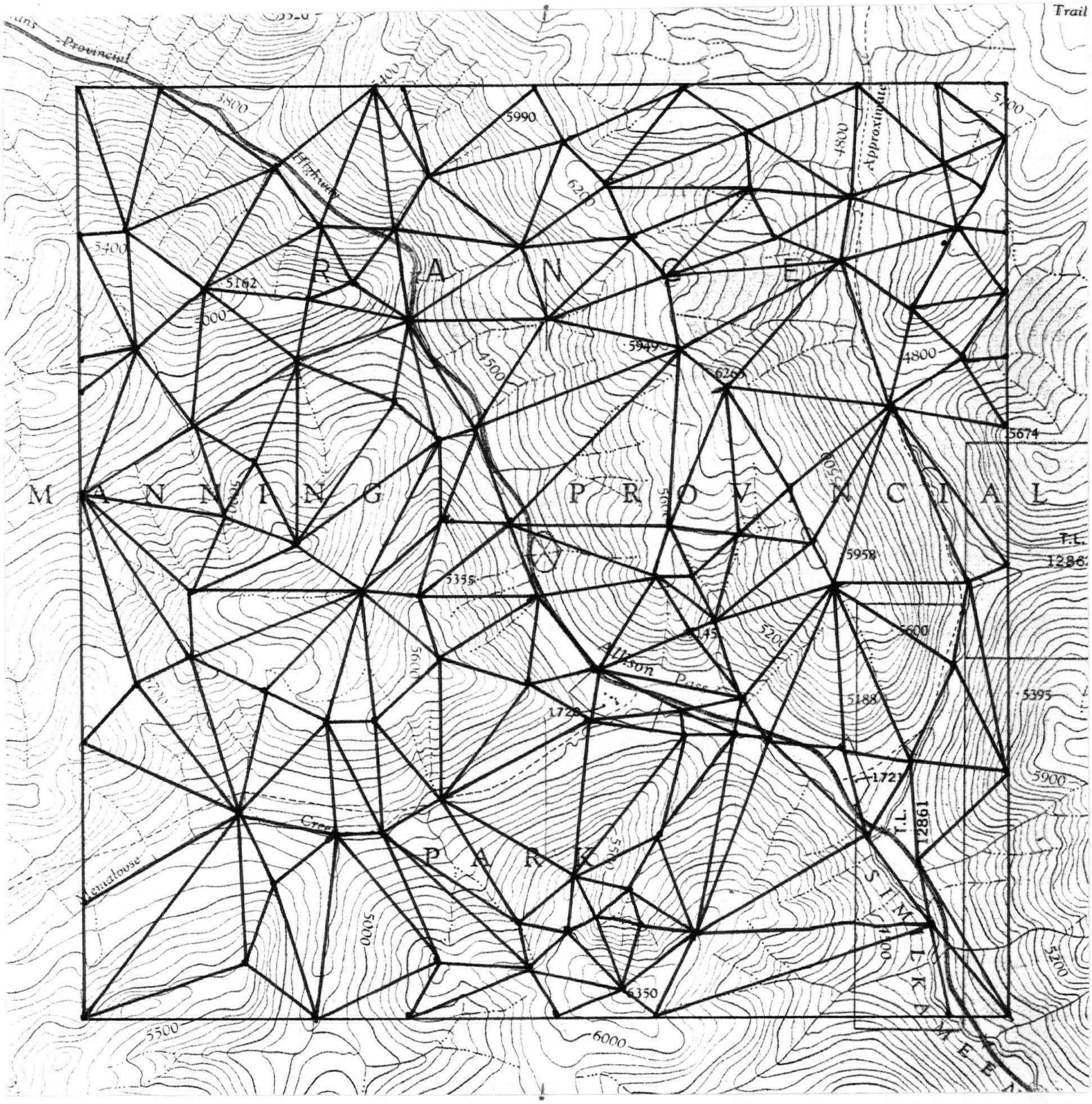




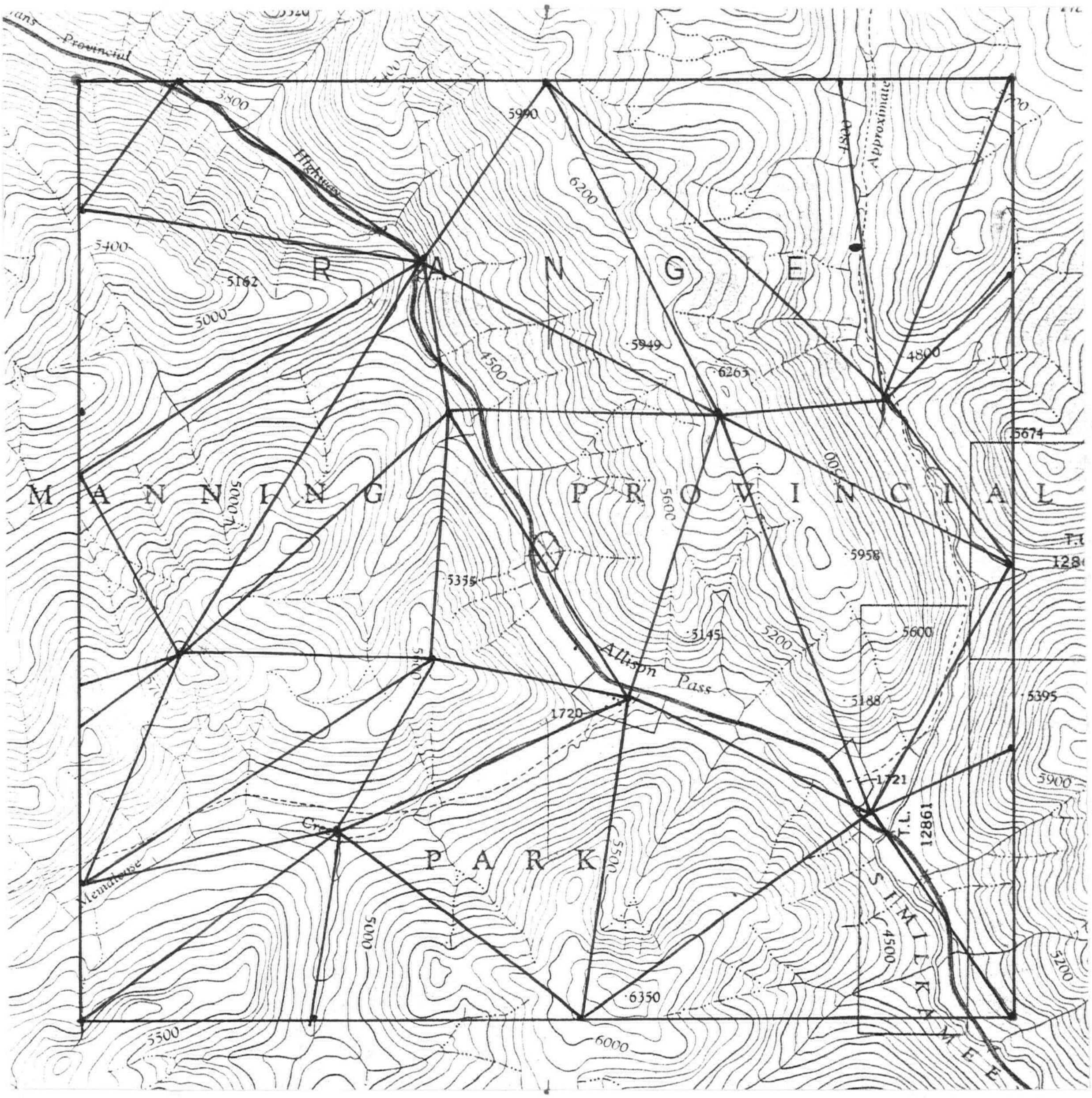
Samples 11b (left) and 11c (above), Ptarmigan Creek map-area (83 D/10W)



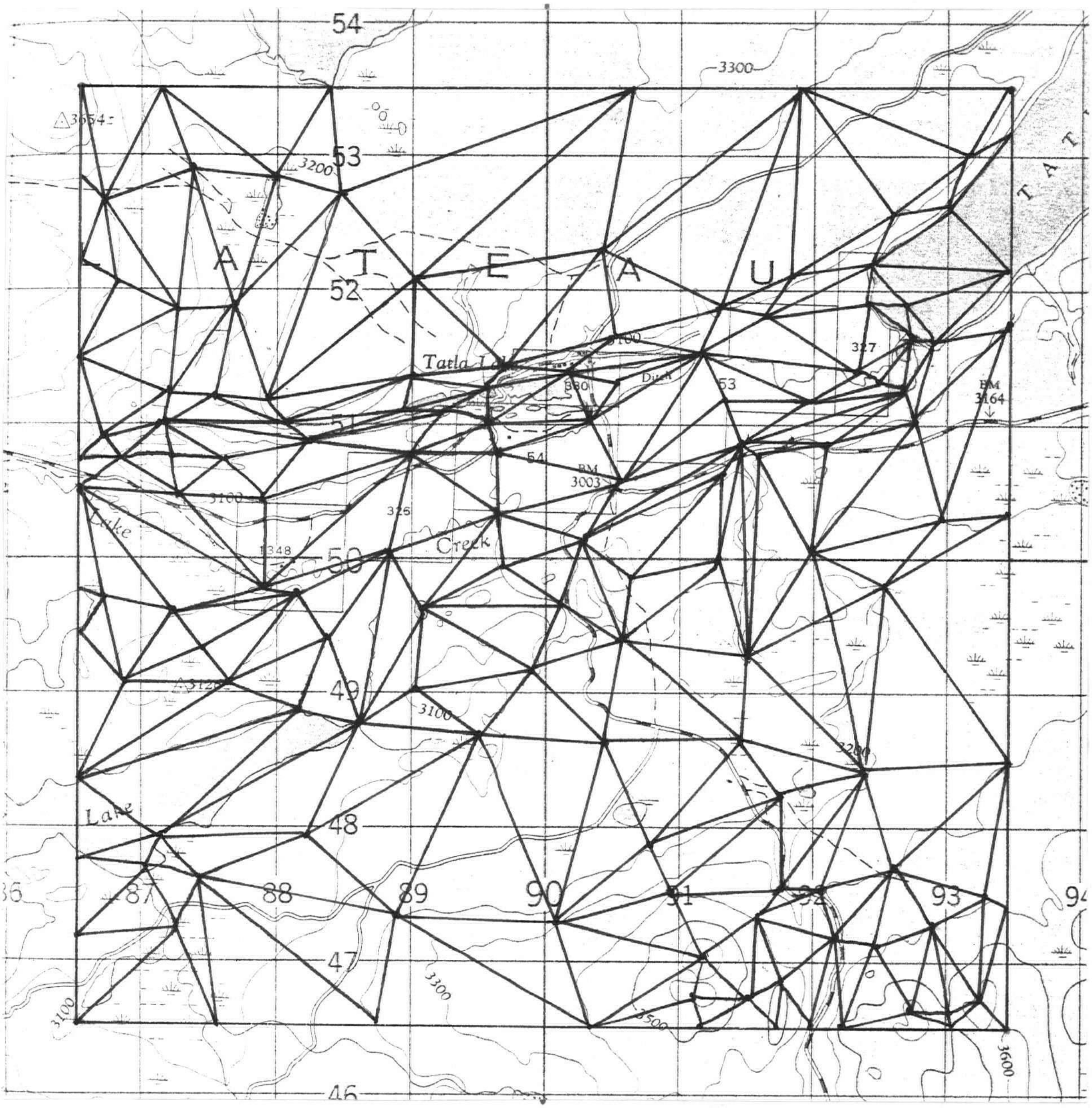
Sample 11d, Ptarmigan Creek map-area (83 D/10W)

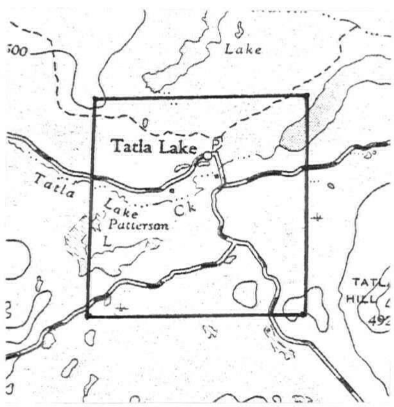


Sample 18a, Manning Park map-area (92 H/2W)

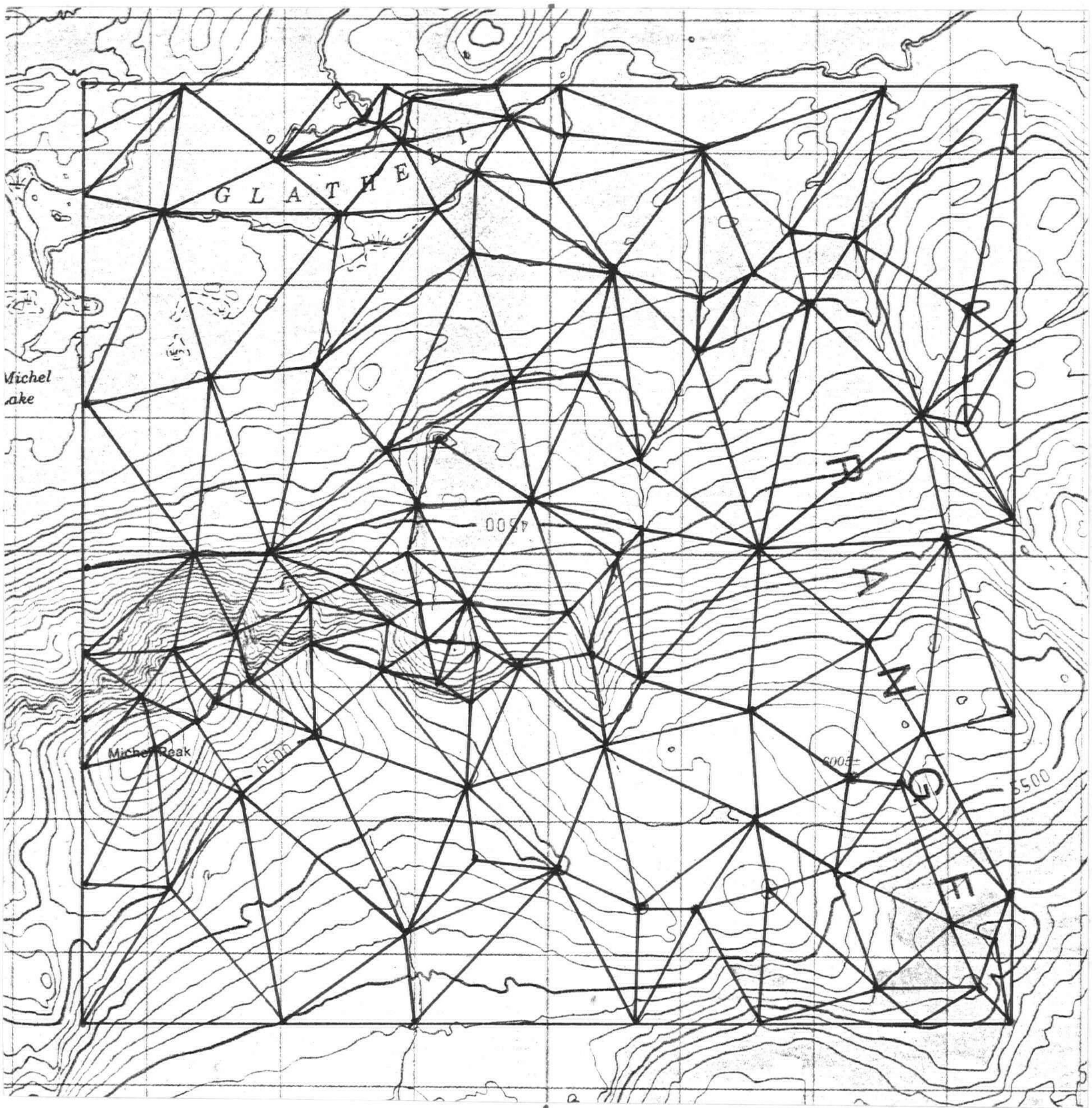


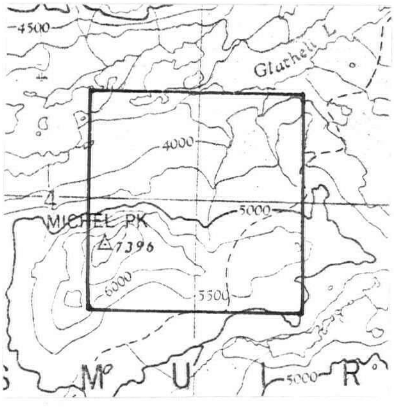
Samples 18b (left) and 18c (above), Manning Park map-area (92 H/2W)



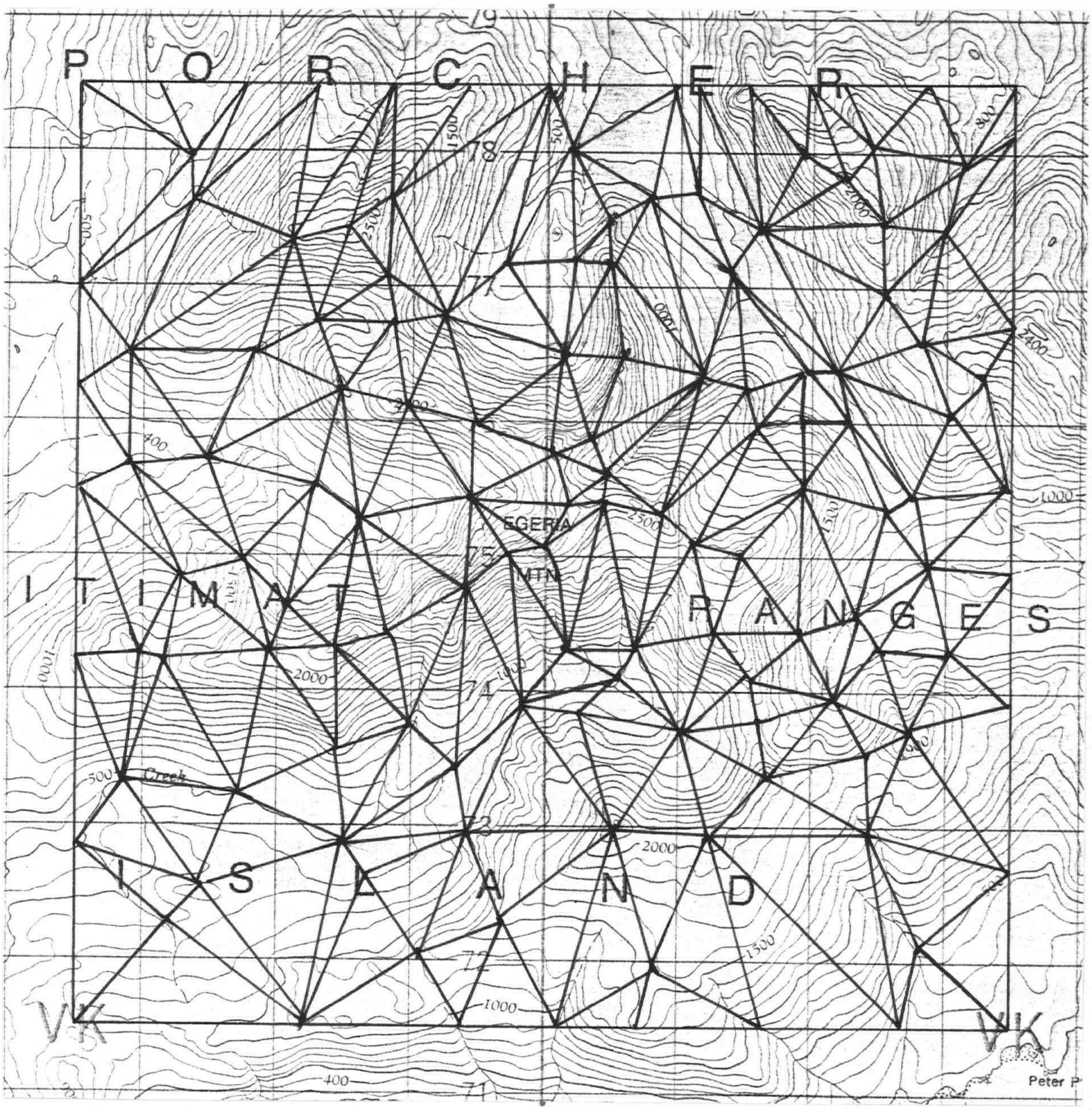


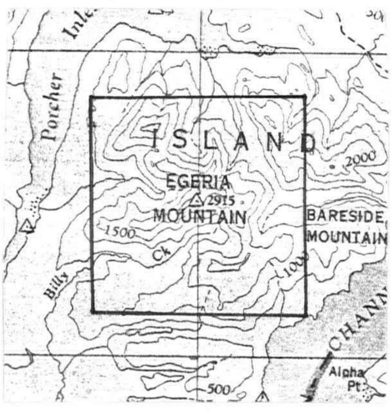
Sample 24, Tatla Lake map-area (92 N/15E)





Sample 31, Ghitezli Lake map-area (93 E/9W)





Sample 41, Oona River map-area (103 G/16W)

Appendix IIIc: Computer Results

This appendix includes the computer output for the thirteen triangular data-set analyses and fourteen grid analyses upon which the comparisons reported in Chapter 6 were based. The titles of these output sheets are self-explanatory.

ILLECILLEWAET (SAMPLE 8)

GENERAL:

```
NUMBER OF POINTS    =                90
NUMBER OF TRIANGLES=                153
TOTAL AREA          = 0.48999296E 08
PERCENT LAKES + SEA=                0.0
NUMBER FOR ANALYSIS=                153
AREA FOR ANALYSIS   = 0.48999296E 08
MEAN TRIANGLE AREA  = 0.32025681E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  877.82  LOCATED AT POINT NUMBER  88
MAXIMUM ELEVATION        = 2743.20  LOCATED AT POINT NUMBER  53
LOCAL RELIEF             = 1865.38
HYPSOMETRIC INTEGRAL     = 0.44691
MEAN SLOPE:
 UNWEIGHTED              = 0.58802
 WEIGHTED BY MAP AREA    = 0.58537
 WEIGHTED BY TRUE AREA   = 0.59797
AREA RATIO               = 1.16841
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =  102.50
 DIP                =   81.70
 L(%)               =   86.91
 K                  =    7.59
 100/K              =   13.18
 ROUGHNESS FACTOR=      13.09

WEIGHTED BY TRUE AREA:
 ORIENTATION        =  116.53
 DIP                =   83.18
 L(%)               =   86.20
 ROUGHNESS FACTOR=      13.80
```

PTARMIGAN CREEK (SAMPLE 11A): ALL POINTS

GENERAL:

```
NUMBER OF POINTS    =              81
NUMBER OF TRIANGLES=              136
TOTAL AREA          = 0.48993283E 08
PERCENT LAKES + SEA=              0.0
NUMBER FOR ANALYSIS=              136
AREA FOR ANALYSIS   = 0.48993285E 08
MEAN TRIANGLE AREA  = 0.36028912E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  695.00  LOCATED AT POINT NUMBER  79
MAXIMUM ELEVATION        = 2404.00  LOCATED AT POINT NUMBER  68
LOCAL RELIEF             = 1709.00
HYPSOMETRIC INTEGRAL     = 0.26341
MEAN SLOPE:
 UNWEIGHTED              = 0.41433
 WEIGHTED BY MAP AREA    = 0.35537
 WEIGHTED BY TRUE AREA   = 0.37800
AREA RATIO               = 1.08917
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =   31.86
 DIP               =   85.76
 L(%)              =   90.97
 K                 =   11.00
 100/K             =    9.09
 ROUGHNESS FACTOR=      9.03

WEIGHTED BY TRUE AREA:
 ORIENTATION       =   60.35
 DIP               =   87.87
 L(%)              =   91.88
 ROUGHNESS FACTOR=      8.12
```

PTARMIGAN CREEK (SAMPLE 11B): FROM 1:250,000 MAP

GENERAL:

```
NUMBER OF POINTS    =              29
NUMBER OF TRIANGLES=               41
TOTAL AREA          = 0.48995776E 08
PERCENT LAKES + SEA=              0.0
NUMBER FOR ANALYSIS=               41
AREA FOR ANALYSIS   = 0.48995776E 08
MEAN TRIANGLE AREA  = 0.11951160E 07
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION         =  701.04  LOCATED AT POINT NUMBER  29
MAXIMUM ELEVATION         = 2362.20  LOCATED AT POINT NUMBER  19
LOCAL RELIEF              = 1661.16
HYPSOMETRIC INTEGRAL      = 0.28530
MEAN SLOPE:
 UNWEIGHTED               = 0.37388
 WEIGHTED BY MAP AREA     = 0.37843
 WEIGHTED BY TRUE AREA    = 0.39364
AREA RATIO                = 1.08822
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =   340.43
 DIP               =    87.29
 L(%)              =    92.24
 K                 =    12.57
 100/K             =     7.95
 ROUGHNESS FACTOR=       7.76

WEIGHTED BY TRUE AREA:
 ORIENTATION       =    13.86
 DIP               =    88.46
 L(%)              =    91.93
 ROUGHNESS FACTOR=       8.07
```

PTARMIGAN CREEK (SAMPLE 11C): APPROX. SAME POINTS AS 11B, BUT 1:50,00

GENERAL:

```
NUMBER OF POINTS    =                 29
NUMBER OF TRIANGLES=                  41
TOTAL AREA          = 0.48998840E 08
PERCENT LAKES + SEA=                 0.0
NUMBER FOR ANALYSIS=                  41
AREA FOR ANALYSIS   = 0.48998840E 08
MEAN TRIANGLE AREA = 0.11951130E 07
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION         =  694.94  LOCATED AT POINT NUMBER  17
MAXIMUM ELEVATION         = 2404.26  LOCATED AT POINT NUMBER  19
LOCAL RELIEF              = 1709.32
HYPSOMETRIC INTEGRAL      = 0.26517
MEAN SLOPE:
 UNWEIGHTED               = 0.37620
 WEIGHTED BY MAP AREA     = 0.36694
 WEIGHTED BY TRUE AREA    = 0.38063
AREA RATIO                = 1.08281
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =    18.38
 DIP               =    89.20
 L(%)              =    92.17
 K                 =    12.46
 100/K             =     8.02
 ROUGHNESS FACTOR=       7.83

WEIGHTED BY TRUE AREA:
 ORIENTATION       =    30.59
 DIP               =    88.05
 L(%)              =    92.41
 ROUGHNESS FACTOR=       7.59
```

PTARMIGAN CREEK (SAMPLE 11D): ALL POINTS

GENERAL:

```
NUMBER OF POINTS     =                85
NUMBER OF TRIANGLES=               143
TOTAL AREA           = 0.48999248E 08
PERCENT LAKES + SEA=              0.15
NUMBER FOR ANALYSIS=               143
AREA FOR ANALYSIS    = 0.48999248E 08
MEAN TRIANGLE AREA = 0.34265206E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION         =  694.94  LOCATED AT POINT NUMBER  85
MAXIMUM ELEVATION         = 2404.26  LOCATED AT POINT NUMBER  70
LOCAL RELIEF              = 1709.32
HYPSOMETRIC INTEGRAL      = 0.26165
MEAN SLOPE:
 UNWEIGHTED               = 0.38116
 WEIGHTED BY MAP AREA     = 0.37070
 WEIGHTED BY TRUE AREA    = 0.39093
AREA RATIO                = 1.09146
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =    41.05
 DIP                =    84.64
 L(%)               =    92.05
 K                  =    12.49
 100/K              =     8.01
 ROUGHNESS FACTOR=        7.95

WEIGHTED BY TRUE AREA:
 ORIENTATION        =    49.65
 DIP                =    87.33
 L(%)               =    91.69
 ROUGHNESS FACTOR=        8.31
```

MANNING PARK(SAMPLE 19): A- 1:5C,CCO SCALE "HIGH RESOLUTION"

GENERAL:

```
NUMBER OF POINTS      =             119
NUMBER OF TRIANGLES=                207
TOTAL AREA          = 0.48999072E 08
PERCENT LAKES + SEA=                0.0
NUMBER FOR ANALYSIS=                207
AREA FOR ANALYSIS   = 0.48999072E 08
MEAN TRIANGLE AREA  = 0.23671044E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION         = 1057.66  LOCATED AT POINT NUMBER   2
MAXIMUM ELEVATION         = 1935.48  LOCATED AT POINT NUMBER  15
LOCAL RELIEF              =  877.82
HYPSOMETRIC INTEGRAL      = 0.54226
MEAN SLOPE:
 UNWEIGHTED               = 0.38932
 WEIGHTED BY MAP AREA     = 0.39315
 WEIGHTED BY TRUE AREA    = 0.39747
AREA RATIO                = 1.07984
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =    24.16
 DIP                =    89.27
 L(%)               =    92.75
 K                  =    13.72
 100/K              =     7.29
 ROUGHNESS FACTOR=        7.25

WEIGHTED BY TRUE AREA:
 ORIENTATION        =   351.01
 DIP                =    89.52
 L(%)               =    92.61
 ROUGHNESS FACTOR=        7.39
```

MANNING PARK(SAMPLE 13): B- 1:250,000 SCALE MAP

GENERAL:

NUMBER OF POINTS = 25
NUMBER OF TRIANGLES= 32
TOTAL AREA = 0.43999904E 08
PERCENT LAKES + SEA= 0.0
NUMBER FOR ANALYSIS= 32
AREA FOR ANALYSIS = 0.43999904E 08
MEAN TRIANGLE AREA = 0.15312470E 07

GEOMORPHOMETRY:

MINIMUM ELEVATION = 1066.80 LOCATED AT POINT NUMBER 2
MAXIMUM ELEVATION = 1905.00 LOCATED AT POINT NUMBER 3
LOCAL RELIEF = 838.20
HYPSOMETRIC INTEGRAL = 0.51731
MEAN SLOPE:
UNWEIGHTED = 0.26015
WEIGHTED BY MAP AREA = 0.25519
WEIGHTED BY TRUE AREA = 0.25726
AREA RATIO = 1.03582

VECTOR ANALYSIS:

UNWEIGHTED(UNIT VECTORS):
ORIENTATION = 39.82
DIP = 89.27
L(%) = 96.41
K = 26.97
100/K = 3.71
ROUGHNESS FACTOR= 3.59

WEIGHTED BY TRUE AREA:
ORIENTATION = 37.29
DIP = 89.39
L(%) = 96.55
ROUGHNESS FACTOR= 3.45

```
MANNING PARK(SAMPLE 18): C- 1:50,000 SCALE, APPROX. SAME POINTS AS 18B


GENERAL:

NUMBER OF POINTS    =                 25
NUMBER OF TRIANGLES=                  32
TOTAL AREA          = 0.4899904E 08
PERCENT LAKES + SEA=                 0.0
NUMBER FOR ANALYSIS=                  32
AREA FOR ANALYSIS   = 0.4899904E 08
MEAN TRIANGLE AREA = 0.1531247CE 07


GEOMORPHOMETRY:

MINIMUM ELEVATION        = 1066.80  LOCATED AT POINT NUMBER   2
MAXIMUM ELEVATION        = 1889.76  LOCATED AT POINT NUMBER   3
LOCAL RELIEF             =  822.96
HYPSOMETRIC INTEGRAL     = 0.54362
MEAN SLOPE:
 UNWEIGHTED              = 0.30852
 WEIGHTED BY MAP AREA    = 0.29546
 WEIGHTED BY TRUE AREA   = 0.29853
AREA RATIO               = 1.04746


VECTOR ANALYSIS:

UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =   355.51
 DIP               =    88.74
 L(%)              =    95.18
 K                 =    20.11
 100/K             =     4.97
 ROUGHNESS FACTOR=       4.82

WEIGHTED BY TRUE AREA:
 ORIENTATION       =    10.61
 DIP               =    89.32
 L(%)              =    95.48
 ROUGHNESS FACTOR=       4.52
```

TATLA LAKE (SAMPLE 24): INCLUDING LAKES

GENERAL:

```
NUMBER OF POINTS    =            142
NUMBER OF TRIANGLES=             250
TOTAL AREA          = 0.48998929E 08
PERCENT LAKES + SEA=            3.76
NUMBER FOR ANALYSIS=             250
AREA FOR ANALYSIS   = 0.48998928E 08
MEAN TRIANGLE AREA  = 0.19599569E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          =  909.83  LOCATED AT POINT NUMBER   7
MAXIMUM ELEVATION          = 1112.52  LOCATED AT POINT NUMBER 126
LOCAL RELIEF               =  202.69
HYPSOMETRIC INTEGRAL       = 0.26789
MEAN SLOPE:
 UNWEIGHTED                = 0.07470
 WEIGHTED BY MAP AREA      = 0.04772
 WEIGHTED BY TRUE AREA     = 0.04803
AREA RATIO                 = 1.00246
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =    45.52
 DIP                =    89.64
 L(%)               =    99.41
 K                  =   167.99
 100/K              =     0.60
 ROUGHNESS FACTOR=        0.59

WEIGHTED BY TRUE AREA:
 ORIENTATION        =   341.59
 DIP                =    89.77
 L(%)               =    99.76
 ROUGHNESS FACTOR=        0.24
```

TATLA LAKE (SAMPLE 24): EXCLUDING LAKES

GENERAL:

```
NUMBER OF POINTS     =            142
NUMBER OF TRIANGLES=              250
TOTAL AREA           = 0.48999CC8E 08
PERCENT LAKES + SEA=             3.76
NUMBER FOR ANALYSIS=              238
AREA FOR ANALYSIS    = 0.47159CC8E 08
MEAN TRIANGLE AREA = 0.19814706E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          =  909.83  LOCATED AT POINT NUMBER   7
MAXIMUM ELEVATION          = 1112.52  LOCATED AT POINT NUMBER 126
LOCAL RELIEF               =  202.69
HYPSOMETRIC INTEGRAL       = 0.27530
MEAN SLOPE:
 UNWEIGHTED                = 0.07846
 WEIGHTED BY MAP AREA      = 0.04958
 WEIGHTED BY TRUE AREA     = 0.04990
AREA RATIO                 = 1.00255
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =     45.52
 DIP               =     89.63
 L(%)              =     99.38
 K                 =    159.92
 100/K             =      0.63
 ROUGHNESS FACTOR=        0.62

WEIGHTED BY TRUE AREA:
 ORIENTATION       =    341.59
 DIP               =     89.76
 L(%)              =     99.75
 ROUGHNESS FACTOR=        0.25
```

CHITEZLI LAKE (SAMPLE 31): INCLUDING LAKES

GENERAL:

```
NUMBER OF POINTS     =             114
NUMBER OF TRIANGLES=               198
TOTAL AREA           = 0.48999136E 08
PERCENT LAKES + SEA=              4.78
NUMBER FOR ANALYSIS=               198
AREA FOR ANALYSIS    = 0.48999136E 08
MEAN TRIANGLE AREA = 0.24747037E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION         = 1063.75  LOCATED AT POINT NUMBER   2
MAXIMUM ELEVATION         = 2258.57  LOCATED AT POINT NUMBER  72
LOCAL RELIEF              = 1194.82
HYPSOMETRIC INTEGRAL      = 0.33723
MEAN SLOPE:
 UNWEIGHTED               = 0.27514
 WEIGHTED BY MAP AREA     = 0.20259
 WEIGHTED BY TRUE AREA    = 0.21590
AREA RATIO                = 1.03331
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =     7.02
 DIP                =    83.29
 L(%)               =    95.65
 K                  =    22.88
 100/K              =     4.37
 ROUGHNESS FACTOR=        4.35

WEIGHTED BY TRUE AREA:
 ORIENTATION        =     5.83
 DIP                =    85.49
 L(%)               =    97.08
 ROUGHNESS FACTOR=        2.92
```

GHITEZLI LAKE (SAMPLE 21): EXCLUDING LAKES

GENERAL:

```
NUMBER OF POINTS    =              114
NUMBER OF TRIANGLES=               198
TOTAL AREA          = 0.43999152E 08
PERCENT LAKES + SEA=              4.78
NUMBER FOR ANALYSIS=               185
AREA FOR ANALYSIS   = 0.46655408E 08
MEAN TRIANGLE AREA = 0.25219137E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        = 1063.75  LOCATED AT POINT NUMBER   2
MAXIMUM ELEVATION        = 2258.57  LOCATED AT POINT NUMBER  72
LOCAL RELIEF             = 1194.82
HYPSOMETRIC INTEGRAL     = 0.35418
MEAN SLOPE:
 UNWEIGHTED              = 0.29448
 WEIGHTED BY MAP AREA    = 0.21277
 WEIGHTED BY TRUE AREA   = 0.22638
AREA RATIO               = 1.03498
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =     7.02
 DIP                =    82.79
 L(%)               =    95.40
 K                  =    21.61
 100/K              =     4.63
 ROUGHNESS FACTOR=        4.60

WEIGHTED BY TRUE AREA:
 ORIENTATION        =     5.83
 DIP                =    85.27
 L(%)               =    96.95
 ROUGHNESS FACTOR=        3.05
```

```
OCNA RIVER (SAMPLE 41)


GENERAL:

NUMBER OF POINTS    =              138
NUMBER OF TRIANGLES=               240
TOTAL AREA          = 0.48998960E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               240
AREA FOR ANALYSIS   = 0.48998960E 08
MEAN TRIANGLE AREA  = 0.20416231E 06


GEOMORPHOMETRY:

MINIMUM ELEVATION        =    30.48  LOCATED AT POINT NUMBER 131
MAXIMUM ELEVATION        =   899.16  LOCATED AT POINT NUMBER  73
LOCAL RELIEF             =   868.68
HYPSOMETRIC INTEGRAL     = 0.40380
MEAN SLOPE:
 UNWEIGHTED              = 0.39164
 WEIGHTED BY MAP AREA    = 0.38090
 WEIGHTED BY TRUE AREA   = 0.39122
AREA RATIO               = 1.08260


VECTOR ANALYSIS:

UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =  320.17
 DIP                =   88.09
 L(%)               =   92.42
 K                  =   13.14
 100/K              =    7.61
 ROUGHNESS FACTOR=       7.58

WEIGHTED BY TRUE AREA:
 ORIENTATION        =  260.69
 DIP                =   83.72
 L(%)               =   92.39
 ROUGHNESS FACTOR=       7.61
```

ILLECILLEWAET (SAMPLE 8): GRID, NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =              225
NUMBER OF TRIANGLES=               392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA  = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  890.02  LOCATED AT POINT NUMBER 207
MAXIMUM ELEVATION        = 2743.20  LOCATED AT POINT NUMBER  92
LOCAL RELIEF             = 1853.18
HYPSOMETRIC INTEGRAL     = 0.43586
MEAN SLOPE:
 UNWEIGHTED              = 0.52344
 WEIGHTED BY MAP AREA    = 0.52345
 WEIGHTED BY TRUE AREA   = 0.53900
AREA RATIO               = 1.14307
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =  114.94
 DIP               =   83.17
 L(%)              =   88.64
 K                 =    8.78
 100/K             =   11.39
 ROUGHNESS FACTOR=     11.36

WEIGHTED BY TRUE AREA:
 ORIENTATION       =  115.07
 DIP               =   83.23
 L(%)              =   88.10
 ROUGHNESS FACTOR=     11.90
```

ILLECILLEWAET (SAMPLE 8): GRID, NE-SW DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =            225
NUMBER OF TRIANGLES=             392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=             0.0
NUMBER FOR ANALYSIS=             392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA  = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          =  890.02  LOCATED AT POINT NUMBER 207
MAXIMUM ELEVATION          = 2743.20  LOCATED AT POINT NUMBER  92
LOCAL RELIEF               = 1853.18
HYPSOMETRIC INTEGRAL       = 0.43576
MEAN SLOPE:
 UNWEIGHTED                = 0.51843
 WEIGHTED BY MAP AREA      = 0.51844
 WEIGHTED BY TRUE AREA     = 0.53654
AREA RATIO                 = 1.14237
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =  113.05
 DIP                =   83.22
 L(%)               =   88.77
 K                  =    8.88
 100/K              =   11.26
 ROUGHNESS FACTOR=      11.23

WEIGHTED BY TRUE AREA:
 ORIENTATION        =  115.07
 DIP                =   83.23
 L(%)               =   88.15
 ROUGHNESS FACTOR=      11.85
```

PTARMIGAN CREEK (SAMPLE 11): GRID, 1:50,000, NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS   =              225
NUMBER OF TRIANGLES=              392
TOTAL AREA         = 0.43997936E 08
PERCENT LAKES + SEA=              0.0
NUMBER FOR ANALYSIS=              392
AREA FOR ANALYSIS  = 0.43997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  694.94  LOCATED AT POINT NUMBER 225
MAXIMUM ELEVATION        = 2301.24  LOCATED AT POINT NUMBER 199
LOCAL RELIEF             = 1606.30
HYPSOMETRIC INTEGRAL     = 0.27922
MEAN SLOPE:
 UNWEIGHTED              = 0.34367
 WEIGHTED BY MAP AREA    = 0.34369
 WEIGHTED BY TRUE AREA   = 0.36039
AREA RATIO               = 1.07858
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =   58.92
 DIP                =   88.49
 L(%)               =   93.24
 K                  =   14.75
 100/K              =    6.78
 ROUGHNESS FACTOR=       6.76

WEIGHTED BY TRUE AREA:
 ORIENTATION        =   55.62
 DIP                =   87.94
 L(%)               =   92.77
 ROUGHNESS FACTOR=       7.23
```

PTARMIGAN CREEK (SAMPLE 11): GRID, 1:50,000, NE-SW DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =             225
NUMBER OF TRIANGLES=              392
TOTAL AREA         = 0.43997936E 08
PERCENT LAKES + SEA=              0.0
NUMBER FOR ANALYSIS=              392
AREA FOR ANALYSIS  = 0.43997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  694.94  LOCATED AT POINT NUMBER 225
MAXIMUM ELEVATION        = 2301.24  LOCATED AT POINT NUMBER 199
LOCAL RELIEF             = 1606.30
HYPSOMETRIC INTEGRAL     = 0.28054
MEAN SLOPE:
 UNWEIGHTED              = 0.35836
 WEIGHTED BY MAP AREA    = 0.35837
 WEIGHTED BY TRUE AREA   = 0.37152
AREA RATIO               = 1.07932
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION      =    58.64
 DIP              =    88.39
 L(%)             =    93.07
 K                =    14.40
 100/K            =     6.95
 ROUGHNESS FACTOR=      6.93

WEIGHTED BY TRUE AREA:
 ORIENTATION      =    55.62
 DIP              =    87.94
 L(%)             =    92.71
 ROUGHNESS FACTOR=      7.29
```

PTARMIGAN CREEK (SAMPLE 11): GRID, 1:250,000, NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =             225
NUMBER OF TRIANGLES=              392
TOTAL AREA         = 0.48997936E 08
PERCENT LAKES + SEA=              0.0
NUMBER FOR ANALYSIS=              392
AREA FOR ANALYSIS  = 0.48997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION         =  701.04  LOCATED AT POINT NUMBER 225
MAXIMUM ELEVATION         = 2362.20  LOCATED AT POINT NUMBER 199
LOCAL RELIEF              = 1661.16
HYPSOMETRIC INTEGRAL      = 0.27464
MEAN SLOPE:
 UNWEIGHTED               = 0.35458
 WEIGHTED BY MAP AREA     = 0.35460
 WEIGHTED BY TRUE AREA    = 0.37275
AREA RATIO                = 1.08195
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION      =    53.01
 DIP              =    88.65
 L(%)             =    93.01
 K                =    14.26
 100/K            =     7.01
 ROUGHNESS FACTOR=      6.99

WEIGHTED BY TRUE AREA:
 ORIENTATION      =    51.01
 DIP              =    88.04
 L(%)             =    92.48
 ROUGHNESS FACTOR=      7.52
```

PTARMIGAN CREEK (SAMPLE 11): GRID, 1:250,000, NE-SW DIAGONALS

GENERAL:

```
NUMBER OF POINTS   =             225
NUMBER OF TRIANGLES=             392
TOTAL AREA         = 0.48997936E 08
PERCENT LAKES + SEA=             0.0
NUMBER FOR ANALYSIS=             392
AREA FOR ANALYSIS  = 0.48997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  701.04  LOCATED AT POINT NUMBER 225
MAXIMUM ELEVATION        = 2362.20  LOCATED AT POINT NUMBER 199
LOCAL RELIEF             = 1661.16
HYPSOMETRIC INTEGRAL     = 0.27589
MEAN SLOPE:
 UNWEIGHTED              = 0.36768
 WEIGHTED BY MAP AREA    = 0.36769
 WEIGHTED BY TRUE AREA   = 0.38229
AREA RATIO               = 1.08274
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION      =    53.30
 DIP              =    88.52
 L(%)             =    92.83
 K                =    13.92
 100/K            =     7.19
 ROUGHNESS FACTOR=      7.17

WEIGHTED BY TRUE AREA:
 ORIENTATION      =    51.01
 DIP              =    88.04
 L(%)             =    92.41
 ROUGHNESS FACTOR=      7.59
```

MANNING PARK (SAMPLE 18): GRID, NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =                 225
NUMBER CF TRIANGLES=                  392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=                  0.0
NUMBER FOR ANALYSIS=                  392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA  = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          = 1066.80   LOCATED AT POINT NUMBER    2
MAXIMUM ELEVATION          = 1889.76   LOCATED AT POINT NUMBER    8
LOCAL RELIEF               =  822.96
HYPSOMETRIC INTEGRAL       = 0.56589
MEAN SLOPE:
 UNWEIGHTED                = 0.33108
 WEIGHTED BY MAP AREA      = 0.33109
 WEIGHTED BY TRUE AREA     = 0.33845
AREA RATIO                 = 1.06347
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =  343.67
 DIP                =   89.39
 L(%)               =   94.25
 K                  =   17.33
 100/K              =    5.77
 ROUGHNESS FACTOR=       5.75

WEIGHTED BY TRUE AREA:
 ORIENTATION        =  350.60
 DIP                =   89.34
 L(%)               =   94.04
 ROUGHNESS FACTOR=       5.96
```

MANNING PARK (SAMPLE 18): GRID, NE-SW DIAGONALS

GENERAL:

```
NUMBER OF POINTS   =              225
NUMBER OF TRIANGLES=              392
TOTAL AREA         = 0.48997936E 08
PERCENT LAKES + SEA=              0.0
NUMBER FOR ANALYSIS=              392
AREA FOR ANALYSIS  = 0.48997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        = 1066.80  LOCATED AT POINT NUMBER    2
MAXIMUM ELEVATION        = 1889.76  LOCATED AT POINT NUMBER    8
LOCAL RELIEF             =  822.96
HYPSOMETRIC INTEGRAL     = 0.56691
MEAN SLOPE:
 UNWEIGHTED              = 0.33473
 WEIGHTED BY MAP AREA    = 0.33475
 WEIGHTED BY TRUE AREA   = 0.34135
AREA RATIO               = 1.06361
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =   351.72
 DIP               =    89.36
 L(%)              =    94.21
 K                 =    17.23
 100/K             =     5.80
 ROUGHNESS FACTOR=       5.79

WEIGHTED BY TRUE AREA:
 ORIENTATION       =   350.60
 DIP               =    89.34
 L(%)              =    94.03
 ROUGHNESS FACTOR=       5.97
```

TATLA LAKE (SAMPLE 24): GRID NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =              225
NUMBER OF TRIANGLES=               392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA  = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          =  909.83  LOCATED AT POINT NUMBER  30
MAXIMUM ELEVATION          = 1097.28  LOCATED AT POINT NUMBER   1
LOCAL RELIEF               =  187.45
HYPSOMETRIC INTEGRAL       = 0.29819
MEAN SLOPE:
 UNWEIGHTED                = 0.04081
 WEIGHTED BY MAP AREA      = 0.04081
 WEIGHTED BY TRUE AREA     = 0.04087
AREA RATIO                 = 1.00130
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =  348.38
 DIP               =   89.80
 L(%)              =   99.87
 K                 =  740.08
 100/K             =    0.14
 ROUGHNESS FACTOR=      0.13

WEIGHTED BY TRUE AREA:
 ORIENTATION       =  348.59
 DIP               =   89.79
 L(%)              =   99.87
 ROUGHNESS FACTOR=      0.13
```

TATLA LAKE (SAMPLE 24): GRID NE-SW DIAGONALS

GENERAL:

```
NUMBER OF POINTS   =               225
NUMBER OF TRIANGLES=               392
TOTAL AREA         = 0.48997936E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               392
AREA FOR ANALYSIS  = 0.48997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        =  909.83  LOCATED AT POINT NUMBER  30
MAXIMUM ELEVATION        = 1097.28  LOCATED AT POINT NUMBER   1
LOCAL RELIEF             =  187.45
HYPSOMETRIC INTEGRAL     = 0.29680
MEAN SLOPE:
 UNWEIGHTED              = 0.03935
 WEIGHTED BY MAP AREA    = 0.03935
 WEIGHTED BY TRUE AREA   = 0.03941
AREA RATIO               = 1.00130
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION      =  348.33
 DIP              =   89.79
 L(%)             =   99.87
 K                =  743.52
 100/K            =    0.13
 ROUGHNESS FACTOR=     0.13

WEIGHTED BY TRUE AREA:
 ORIENTATION      =  348.59
 DIP              =   89.79
 L(%)             =   99.87
 ROUGHNESS FACTOR=     0.13
```

GHITEZLI LAKE (SAMPLE 31): GRID, NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =              225
NUMBER OF TRIANGLES=               392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          = 1063.75  LOCATED AT POINT NUMBER  17
MAXIMUM ELEVATION          = 2255.52  LOCATED AT POINT NUMBER 152
LOCAL RELIEF               = 1191.77
HYPSOMETRIC INTEGRAL       = 0.33395
MEAN SLOPE:
 UNWEIGHTED                = 0.18685
 WEIGHTED BY MAP AREA      = 0.18686
 WEIGHTED BY TRUE AREA     = 0.19436
AREA RATIO                 = 1.02803
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =     2.44
 DIP                =    85.89
 L(%)               =    97.73
 K                  =    43.96
 100/K              =     2.27
 ROUGHNESS FACTOR=        2.27

WEIGHTED BY TRUE AREA:
 ORIENTATION        =     2.26
 DIP                =    85.58
 L(%)               =    97.56
 ROUGHNESS FACTOR=        2.44
```

GHITEZLI LAKE (SAMPLE 31): GRID, NE-SW DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =              225
NUMBER OF TRIANGLES=               392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA  = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION        = 1063.75  LOCATED AT POINT NUMBER  17
MAXIMUM ELEVATION        = 2255.52  LOCATED AT POINT NUMBER 152
LOCAL RELIEF             = 1191.77
HYPSOMETRIC INTEGRAL     = 0.33431
MEAN SLOPE:
 UNWEIGHTED              = 0.18474
 WEIGHTED BY MAP AREA    = 0.18475
 WEIGHTED BY TRUE AREA   = 0.19240
AREA RATIO               = 1.02801
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION       =    2.82
 DIP               =   85.88
 L(%)              =   97.74
 K                 =   44.08
 100/K             =    2.27
 ROUGHNESS FACTOR=      2.26

WEIGHTED BY TRUE AREA:
 ORIENTATION       =    2.26
 DIP               =   85.58
 L(%)              =   97.57
 ROUGHNESS FACTOR=      2.43
```

OONA RIVER (SAMPLE 41): GRID, NW-SE DIAGONALS

GENERAL:

```
NUMBER OF POINTS    =              225
NUMBER OF TRIANGLES=               392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=               0.0
NUMBER FOR ANALYSIS=               392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA  = 0.12499469E 06
```

GEOMORPHOMETRY:

```
MINIMUM ELEVATION          =    30.48  LOCATED AT POINT NUMBER 225
MAXIMUM ELEVATION          =   853.44  LOCATED AT POINT NUMBER 113
LOCAL RELIEF               =   822.96
HYPSOMETRIC INTEGRAL       = 0.41974
MEAN SLOPE:
 UNWEIGHTED                = 0.32444
 WEIGHTED BY MAP AREA      = 0.32445
 WEIGHTED BY TRUE AREA     = 0.33495
AREA RATIO                 = 1.06524
```

VECTOR ANALYSIS:

```
UNWEIGHTED(UNIT VECTORS):
 ORIENTATION        =  266.80
 DIP                =   88.77
 L(%)               =   94.20
 K                  =   17.20
 100/K              =    5.81
 ROUGHNESS FACTOR=       5.80

WEIGHTED BY TRUE AREA:
 ORIENTATION        =  263.80
 DIP                =   88.80
 L(%)               =   93.90
 ROUGHNESS FACTOR=       6.10
```

```
OONA RIVER (SAMPLE 41): GRID, NE-SW DIAGONALS


GENERAL:

NUMBER OF POINTS    =               225
NUMBER OF TRIANGLES=                392
TOTAL AREA          = 0.48997936E 08
PERCENT LAKES + SEA=                0.0
NUMBER FOR ANALYSIS=                392
AREA FOR ANALYSIS   = 0.48997936E 08
MEAN TRIANGLE AREA = 0.12499469E 06


GEOMORPHOMETRY:

MINIMUM ELEVATION           =   30.48  LOCATED AT POINT NUMBER 225
MAXIMUM ELEVATION           =  853.44  LOCATED AT POINT NUMBER 113
LOCAL RELIEF                =  822.96
HYPSOMETRIC INTEGRAL        = 0.42002
MEAN SLOPE:
 UNWEIGHTED                 = 0.32632
 WEIGHTED BY MAP AREA       = 0.32634
 WEIGHTED BY TRUE AREA      = 0.33638
AREA RATIO                  = 1.06533


VECTOR ANALYSIS:

UNWEIGHTED(UNIT VECTORS):
 ORIENTATION          =  263.92
 DIP                  =   88.80
 L(%)                 =   94.18
 K                    =   17.13
 100/K                =    5.84
 ROUGHNESS FACTOR=         5.82

WEIGHTED BY TRUE AREA:
 ORIENTATION          =  263.80
 DIP                  =   88.80
 L(%)                 =   93.89
 ROUGHNESS FACTOR=         6.11
```