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UNIVERSITY OF ALBERTA

LANDFORM MAPPING, ANALYSIS AND CLASSIFICATION USING DIGITAL TERRAIN MODELS

by

GESCHE SCHMID-MCGIBBON

A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements for the degree of Doctor of Philosophy

DEPARTMENT OF GEOGRAPHY

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Abstract

Landform has been used as a key modifier in several land system classifications in Canada. Little attention has been placed on a precise definition and a reliable classification of landform categories. Landform categories have most commonly been mapped as qualitative modifiers using airphoto interpretation. Such classification lacked an accurate determination of quantitative modifiers required for use in numerical analysis as implemented in geographic information systems.

An attempt is made with this research to determine landform categories more accurately using digital terrain models (DTMs) and numerical analysis techniques. Alberta 1:20,000 digital elevation models (DEMs) were used to map, analyse and classify landform categories delineated on 1:50,00 soil and surficial geology landform maps for an area located in east central Alberta in the County of St. Paul. Soil and geology landform categories were analysed according to statistical measurements derived from DTM distributions of local relief, slope gradient, azimuth and curvature. The result of the analysis suggests that landform categories can and have to be labelled more precisely than they are currently using statistical measurements of mean, mode and variance.

For the generation of landform maps, landform categories were interpreted from classed and continuous grey scale DTMs of local relief, slope gradient, curvature and relative radiance. In a further step, the manual interpretation technique was replaced by semiautomated and automated mapping and classification techniques. Special emphasis was placed on the consideration of context in landform mapping and classification which is essential for the determination of landform patterns. Consequently, the landforms are mapped and classified not only according to morphometric characteristics derived from single grid points but also according to contextual information derived from neighbourhoods. Individual morphometric modifiers were mapped using a modal filtering technique over large neighbourhoods. Relative variance was introduced as a useful measure to determine the neighbourhood size according to texture. Local relief was derived by calculating the elevation range over neighbourhood sizes determined according to grain analysis. The application of these neighbourhood processing functions improved the overall readability of the individual morphometric maps by generating large homogeneous landform units.

In a final step, a frequency-based context classifier only used previously in urban land use classification was introduced for the first time to landform modelling. Frequency counts of classed morphometric modifiers were extracted from neighbourhoods and formed the variable base for a discriminant analysis used to classify landform categories. The resulting landform classification proved to be a step forward in the automated generation of meaningful landform maps. The research shows that landform classifications are improved by using digital terrain models and by applying numerical analysis techniques although the impact of the human analyst remains a vital part of the interpretation and mapping process.

Preface

This research focuses exclusively on the analysis, interpretation and classification of digital terrain models. The author greatly appreciates the existence of these data sets because of her inability to see in three dimensions. As a consequence, the advantages of airphoto interpretation cannot be fully acknowledged.

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1. Introduction

1.1 Rationale of the Research

This thesis provides a systematic and detailed analysis of landform characteristics and focuses on the development and application of methods for mapping and classifying landform objectively and accurately using digital terrain models. The development and application of such methods is of importance because landform is recognized as one of the controlling factors in the development of ecosystems. Landform patterns affect the flow of material, energy and organisms. As a result, changes in landform patterns are used to predict changes in patterns of other landscape parameters such as soil, geology and vegetation mapped in land system classifications (Brink *et al.*, 1966). The concept of land system classification, which has been implemented in Great Britain (Webster and Beckett, 1970), Australia (Christian and Stewart, 1968) and several other countries (Mitchell, 1991), has also been adopted in Canada by the Ecological (formerly Biophysical) Land Classification System (Lacate, 1969; Wiken and Ironside, 1977).

The Ecological Land Classification System was established in Canada to provide the Canada Land Inventory with land suitability and capability information for various land uses. Guidelines, given by the Ecological (Biophysical) Landform Classification System (Lacate, 1969) for mapping recurrent patterns of landform, soil, geomorphology, vegetation, and hydrology were employed in Canada by various organisations, such as the Canadian Wildlife Service, the Canadian Forestry Service, the Canadian Soil Survey, and the Geological Survey of Canada (Wiken, 1980). One of the main objectives of the Canada Committee on Ecological Land Classification (CCELC), which was formed to coordinate the involvement of the various organisations, was to promote the application of a uniform ecological approach to land classification (CCELC, 1976). To evaluate whether or not such a uniform approach has been achieved, existing land classifications were tested for compatibility in this thesis. In order not to exceed the scope of this dissertation, the research is limited to the investigation of landform classification compatibility. Landform was selected as a parameter because it is used as key modifier in several Canadian Land System Classifications, such as the Canadian System of Soil Classification (Expert Committee on Soil Survey (E.C.S.S.), 1987a), the Terrain

Classification System (Fulton *et al.*, 1974; Howes and Kenk, 1988) and the Ecological Land Classification (Wiken, 1980).

To produce compatible landform classifications, two conditions must be satisfied: first, landform categories must be defined precisely and the definitions must be comparable between the various surveys; and, second, reliable data sources and methods must be used to generate reproducible results. Current landform classifications do not meet these requirements for two reasons; first, landform classifications are still conceptual in scope and need further development to provide a rigid parametric definition of landform categories (E.C.S.S., 1987a; Fulton *et al.*, 1974); and, second, landform categories are mapped using airphoto interpretation techniques followed by field surveys. The results of the airphoto interpretation, however, are dependent on the quality of the airphotos and on the analyst's subjective judgement, expertise, and knowledge of the area (Webster and Beckett, 1970; Laut and Paine, 1982). As a result, the delineation of landform categories varies from analyst to analyst and from user to user with each individual unable to identify a single parameter which may have caused the variation.

To define landform categories more accurately and rigidly and to produce a more objective landform classification, quantitative analysis and automated classification techniques could be implemented. Numerical methods have been used in quantitative landform analysis since the beginning of the quantitative revolution in geography in the 1950's. However, the implementation of an extensive statistical analysis required to solve problems of spatial complexity, such as landform modelling and classification, was only possible with the development of computers (Dobson, 1983). Furthermore, the availability of digital data sources such as digital terrain models (DTMs) facilitates a detailed numerical analyses of landform classifications. DTMs have been recognized as the single most important digital data source for presenting landform characteristics (Mark, 1975; Evans, 1980; Pike, 1988; Weibel and Heller, 1991). The development of computer technology, the generation of digital data sources, and the conversion of quantitative analysis and display techniques into computer programs provide the technical tools of a geographic information system and enable the application of numerical techniques for landform mapping, analysis and classification as implemented in this thesis.

1.2 Research Objectives

The thesis focuses on the application of numerical techniques using digital terrain models to address the following two objectives:

1. to provide a systematic, detailed analysis of existing Canadian landform classifications based on DTM distributions using two case studies, a soil landform classification and a geology landform classification
2. to map and classify landform categories from DTMs using manual, semiautomated and automated modelling and interpretation techniques.

The first objective has two purposes: first, to determine which statistical parameters derived from DTM distributions can be used to define landform categories most accurately; and, second, to assess the compatibility of various Canadian landform classifications carried out for the same area by different surveys. Attempts have been made to evaluate the accuracy of landform parameters in individual Canadian land system classifications (Niemann, 1988; Sheard and Rowe, 1983) but none of these have assessed the compatibility of landform classifications between different land systems in such a systematic and detailed analysis as addressed in this research. Based on the analysis presented in this thesis, an attempt was made to provide guidelines for refining the existing landform classification definitions.

The second objective is directed to improving the methods used to map and classify landform categories. The approach adopted is divided into three processing steps: first, visual (manual) interpretation of landform categories from digital terrain model images and maps; second, mapping of individual landform characteristics using neighbourhood processing functions (this step includes the determination of neighbourhood sizes according to homogeneous landform patterns); and, third, automated classification of landform categories from digital terrain model distributions using a contextual instead of a point classifier. The first processing step is used as a control to determine how the landform classifications may be improved by replacing airphotos with digital terrain model images and maps while retaining the manual interpretation process. The two subsequent processing steps present a shift in the decision making process from the human interpreter to the computer. In these processing steps, special attention is given to mapping and classifying DTM data in the spatial context in which they occur. The use of spatial statistics in geographic information systems, which define spatial dependence by exploring data in their spatial context, has been recognized as a necessity for the analysis of geographical data, such as landform patterns (Goodchild, 1992). The application of spatial analysis and modelling techniques, however, is complex. In addition, some of the techniques used in this research were applied in landform modelling for the first time. For these reasons, a substantial portion of the thesis focuses on the description of methods.

One of the objectives of the mapping, analysis and classification processes developed in recent years, and implemented in this thesis, has been to copy the ability of the human interpreter to recognize landform pattern differences. These analysis techniques were designed to build the function of the eye/brain system into the automated modelling process (Harris, 1980). Imhof (1982, p.357, 358) denies that computer modelling can replace the work of a cartographer, stating that

> "the content and graphical structure of a complex demanding map image can never be rendered in a completely automatic way. Machines, equipment, electronic brains posses neither geographical judgement nor graphic-aesthetic sensitivity. Thus the content and graphic creation remains essentially reserved for the critical work of the compiler and drawer of a map".

Based on Imhof's statement, the derived maps are judged against two criteria:

1. Does the automated mapping and classification process replace the manual interpretation process or is further interpretation of the automatically produced maps required?
2. How much and what kind of human interaction is necessary during the automated classification process to produce a complex meaningful landform map?

1.3 Structure of the Thesis

The thesis is divided into eight chapters. Chapter one has introduced the rationale for the research and the research objectives. A detailed literature review is presented separately in Chapter two. The literature review defines the terminology used in the thesis, provides a brief historical overview on the development of landform analysis and classification methods, describes the generation of digital elevation models (DEMs) and their derivatives, and presents examples of landform mapping in Canada.

In Chapter three, the study area and the data sources, such as soil and geology maps, are introduced and the transformation of landform information portrayed on the soil and the geology map into digital data sets is described. The chapter includes also a description of the 1:20,000 Alberta DEM project and the generation of DTMs of local relief, slope gradient, slope azimuth, and downslope curvature derived from the 1:20,000 Alberta DEMs. The DTMs described in Chapter three form the main components for the research. For this reason, the DTMs are presented at the center of a flow diagram portraying the structure of the dissertation (Figure 1.1). The methods applied in the research are directed from the center towards the margins of the diagram. At the margins, the landform data sets, which result from the modelling processes, are compared with the geology and soil landform data sets.

The four principal methods implemented in the research form the basis for the main chapters of the thesis (Chapter 4 to 7). These methods are presented clockwise from the top in Figure 1.1. Each of the chapters stands as an independent unit and is comprised of an introduction, methods, analysis and summary section. In Chapter four, mapping of local relief, slope gradient, downslope curvature and hillshading DTMs in the form of classed and continuous grey scale images and maps is described. From these images and maps, landform categories are delineated using conventional image interpretation techniques. In Chapter five, the application of interpretation techniques proceeds one step further and the incorporation of contextual information into the mapping process is described. Local relief maps, and filtered slope gradient and downslope curvature maps are derived by using neighbourhood processing functions after the size of the neighbourhood are determined from the analysis of texture and grain. The quantitative analysis of existing landform classifications is explained in chapter six. In this analysis, a geology landform classification is compared with a soil landform classification and the individual landform categories are defined according to statistical measurements derived from DTM distributions of local relief, slope gradient, azimuth and downslope curvature. The introduction of a frequency-based contextual classifier to automated landform classification, which has only been previously used in remote sensing analysis to classify urban land uses, is presented in Chapter seven. The contextual information used in the landform classification consist of DTM class frequency counts derived from neighbourhoods. The landform classification itself is based on a discriminant analysis of supervised training field selections.

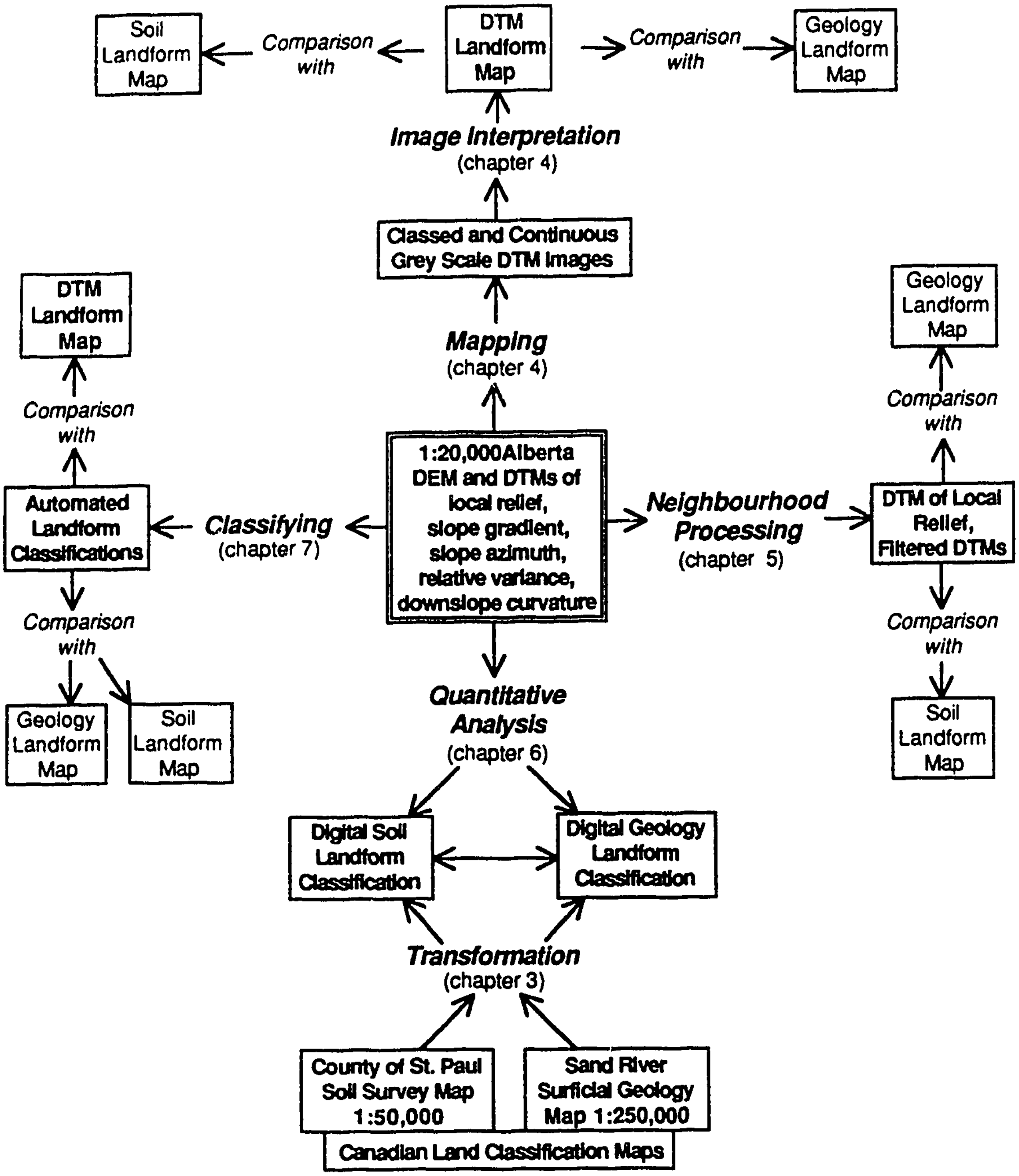


Figure 1.1. Research flow diagram

A synthesis of the summary sections concluding each chapter and the final conclusions of the thesis are presented in Chapter eight. Future research directed towards the improvement of methods and further mapping and classification applications complete the closing section of the thesis.

2. Background Information and Literature Review

2.1 Landform Definition

Landform is defined as the morphology and character of a land surface that results from the interaction of physical processes upon the surface material (Whittow, 1984). More specifically, for use in the Canadian Ecological (Biophysical) Land Classification, landform as characterized by Lacate (1969) consists of areas of land or topographic features that are defined in terms of their slopes and slope patterns, the material that produces the relief and, wherever possible, their mode of origin. In a general description, landform constitutes not only the configuration and structure of the form but also the composition, genesis and age of the form. These broad definitions of landform and landform classification have led to a variety of interpretations in the literature (Verstappen, 1983; Cooke and Doornkamp, 1974; 1990). The term landform, as used in this research, will be related strictly to the morphology of landform, as described by morphometry and morphography. Morphometry is defined as the numerical description of form using quantitative landform modifiers, such as slope gradient or local relief, whereas morphography is defined by the verbal description of landform, such as *ridged* and *hummocky*, which are also referred to as surface expression (E.C.S.S., 1987a; Howes and Kenk, 1988). Processes and material are excluded from this study. However, in an interpretation, a characteristic landform can reveal much about the material, and the geologic and geomorphic processes which shaped the landform (Lacate, 1969; Pike, 1988). Instead of only describing the form morphologically, the feature can later be differentiated genetically. For example, the landform descriptor *ridged* can be associated with sand dunes, end moraines or flutings.

The term *terrain* has been used parallel to the term *landform*, especially by geologists (Howes and Kenk, 1988; Fulton et al., 1974) and engineers (Grant, 1975). Webster and Beckett (1970) used the term *terrain* and *land* synonymously. According to Van Zuidam (1986), the term *land* includes the abiotic and biotic components of the earth surface whereas *terrain* deals with the abiotic components only. Landform was interpreted by Van Zuidam (1986, p. 10)"as terrain units for which geomorphologic terms can be applied". In this thesis, the term *landform* refers to a specific landform as characterized by the Canadian System of Soil Classification (E.C.S.S., 1987a), whereas the term *terrain* is used more generally, referring to the land surface as a whole.

2.2 Principles of Mapping and Classification

Maps are abstract models of reality and present a graphical display of spatial relationships (Robinson *et al.*, 1978). On the one hand, landform maps are products of terrain analysis and interpretation; and, on the other hand, landforms and their spatial relationships can be interpreted from DTM maps using visualization techniques (Weibel and Heller, 1990; 1991). Both processes will be referred to in this thesis.

The process of mapping involves the structurization and generalization of data from reality (Kraak, 1989). Structurization involves the determination of topological relationships between data elements whereas simplification and classification are elements of a generalization process (Robinson *et al.*, 1978). Simplification is achieved by reducing or eliminating detail from a data complex, for example through filtering. In a classification process, landform elements having common characteristics are grouped to form homogeneous units. As Mabbutt (1968, p.11) stated, "landform classification imposes a framework of generalization about land which enables common characteristics to be defined and described". Conventionally, classification as used in numerical taxonomy is based on the grouping of discrete, independent and unambiguously identifiable objects (Mather, 1972). The homogeneity of the classes is defined in terms of attribute homogeneity only. However, Speight (1974) pointed out that the homogeneity of landform includes locational and attribute homogeneity. The principle of locational homogeneity must consider the spatial aspect of the morphometric data missing in conventional classification techniques. Grigg (1967) concluded that regionalization and classification are analogous procedures. Regions can be identified as spatial classes consisting of similar and contiguous individuals. Consequently, regionalization can be interpreted as a classification process imposing contiguity constraints. The principle of attribute and locational homogeneity will be considered for any single- or multi-variable landform classification developed for this thesis.

2.3 Hierarchical Approach to Landform Classification

Most landform map legends are built on a hierarchical approach to landform classification. In the hierarchical approach, the land surface is classified by subdivision or by association into units of different scale. Classification by subdivision divides the entire land surface complex into landform units and further into subunits using an analytical approach. The classification follows a descending hierarchy of successively larger scaled units. Classification by subdivision is applied in the genetic approach to landform classification (Wright, 1972). Classification by association groups landform attributes together according to observable relationships between the landform attributes. The landform attributes are classified into successively smaller scaled units following a hierarchy of ascending order. This synthetic approach to landform classification is mainly used by the landscape and parametric approach discussed below.

Canada adopted a hierarchical approach to the Ecological Land Classification which forms the basis for any Canadian landform classification (Wiken, 1980). The hierarchy of individual landform units arranged according to scale and landform characteristics associated with the landform units are illustrated in Table 2.1. The size of the units is related to the intended production map scale. In this research, the landform units are related to units at the ecosection level, at scales of 1:250,000 to 1:50,000, representing assemblages of local landforms or a local landform.

Many other classification hierarchies similar to the Canadian system have been developed which contain, in most instances, several category levels (Mitchell, 1991). In contrast, Speight (1974) proposed a two unit system used in parametric landform classification consisting of landform elements and landform regions. A landform element is defined as a simply curved, geometric surface without inflection. The concept of slope is essential to the characterization of the element. The landform regions are complex areas of land, typically comprised of a three-dimensional cyclic or repetitive phenomenon in which simple elements recur in toposequences, such as catenas, forming a definable ordered pattern. Relief is the main parameter characterizing a region. Landform elements have been determined by other authors according to morphology or genesis. For example, Savigear (1965), Young(1971) and Ahnert (1970) divided an entire hillslope into smaller slope

Table 2.1. Hierarchy of Eco-Units According to the Canadian Ecological Land Classification (adapted from Wiken (1980) and Valentine (1986))

Hierarchy of Eco-units	General Description	Geomorphological Description	Common Map Scale
Ecoregion	characterized by a distinctive ecological response to climate as expressed by vegetation, soils, water, fauna, etc.	regional landforms or assemblages of regional landforms	1:3,000,000 to 1:1,000,000
Ecodistrict	characterized by a distinctive pattern of relief, geology, geomorphology, vegetation, soils, water and fauna	regional landform or assemblages thereof	1:500,000 to 1:125,000
Ecosection	recurring pattern of terrain, soils, vegetation, waterbodies and fauna	assemblages of local landforms or a local landform	1:250,000 to 1:50,000
Ecosite	relatively uniform parent material, soil and hydrology and a chronosequence of vegetation	local landform or portion thereof	1:50,000 to 1:10,000
Ecoelement	uniform soil, topographical, vegetative and hydrological characteristics	portion of a local landform	1:10,000 to 1:2,500

elements according to geometric measurements, whereas Dalrymple *et al.* (1968) differentiated slope units according to processes acting on a hillslope.

Landform elements, as used in this research, are not related to a predefined form or process but to a predefined size based on a grid cell of a digital terrain model (DTM). The objective of the research is to derive homogeneous regions based on predefined assemblages of landform elements by means of regionalization using numerical classification techniques.

2.4 Landscape versus Parametric Approach to Landform Classification

Three approaches to landform classification have been identified: the genetic approach, the landscape approach and the parametric approach (Mabbutt, 1968). Only the last two, however, are relevant to this thesis and are described in more detail. The landscape approach to landform classification, adopted from the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) (Stewart, 1968), classifies characteristic assemblages and recurring patterns of landform elements by tone, texture, pattern, shape, size and site using airphoto interpretation (Mabbutt, 1968; Webster and Beckett, 1970). Landform units are described as *ridged, fluted* etc., and their analysis is generally qualitative.

The landscape approach is suitable to classify landforms at reconnaissance level because the approach is integrative and holistic (Wright, 1972; Wiken, 1980; Hills, 1976). The units are selected in consideration of their areal identity by association rather than subdivision (Mabbutt, 1968). No redundant data need to be gathered because the whole landscape is explained by a synthesis of attributes. This multipurpose mapping capability of the landscape approach serves many users including geologists, ecologists, soil scientists, and engineers. The approach has been adopted in Canada by the Ecological Landform Classification (Wiken, 1980) and is used by the Terrain Science Division of the Geological Survey (Fulton *et al.*, 1974; Barnett *et al.*, 1977), the Forestry Service (Valentine, 1986; Rowe, 1971) and Soil Survey of Agriculture Canada (Clark, 1976; E.C.S.S.; 1987a). Other countries, such as the former Soviet Union (Isachenko, 1973), the United Kingdom (Webster and Beckett, 1970; Wright, 1972), Australia (Mabbutt, 1968), The Netherlands (Van Zuidam 1986; Verstappen, 1983) and Germany (Leser, 1978) applied similar approaches to classify land systems. Further applications of the landscape approach to qualitative landform analysis and classification can be found in Mitchell (1973, 1991), Ollier (1977), Vink (1983), Van Zuidam (1986) and Way (1973).

The landscape approach has certain disadvantages when used for a more detailed and specific survey (Wright, 1972). First, the holistic approach, which integrates all attributes to a whole, does not allow individual components to be singled out when necessary. Second, the delineation of the land units using airphoto interpretation is subject to the interpreters expertise and knowledge and consequently the reproducibility is not reliable (Mabbutt, 1968; Mitchell, 1991). Third, the landscape approach is based on a descriptive qualitative classification. A descriptive qualitative classification, however, is not suitable for application to computer technology whereas a numerical quantitative classification can be more easily manipulated in geographic information systems and transformed for scientific evaluation in other research projects (Mabbutt, 1968; Wright, 1972; Mitchell, 1973; 1991).

As a result of the inadequacy of the landscape approach in the era of computer technology, the parametric approach was developed to classify landforms on the basis of selected measurable attributes as required in a quantitative analysis (Mabbutt, 1968). In the parametric approach, each attribute or parameter is collected independently, analysed statistically and then combined, depending on the research objective, using a variety of numerical techniques. In the past, the major disadvantage of the parametric approach was the high cost involved in gathering such detailed data sets (Mabbutt, 1968; Wright, 1972). The availability of synoptic digital data sets, such as digital elevation models and satellite data, the introduction of computer technology, and the implementation of various software initiated the development of geographic information systems which revolutionized the application of the parametric approach to landform classification. With the availability of geographic information systems, users can now assemble their own data sets and select the desired manipulation techniques to solve their specific research problems (Strobl, 1988).

The advantages of the parametric approach over the landscape approach are the precision and objectivity of the numerical parameters and the relative ease with which they can be computerized compared to descriptive parameters (Wood and Snell, 1960; Mabbutt, 1968). However, several problems are associated with a parametric approach which must be considered in the research: first, the selection of attributes must be relevant to the classification (Mabbutt, 1968); second, the parameters may vàry in space and time depending on the complexity of attribute relationships (Mabbutt, 1968); and, third, grid cell sizes often mismatch with the pattern size of the landform units (Rowe and Sheard, 1981). The aim of this research is the application of the parametric approach to achieve a more reliable reproduction of a more exactly defined landform classification while incorporating the comprehensiveness of the landscape approach.

2.5 Quantitative Landform Analysis and Classification

One of the first attempt of a quantitative landform analysis was initiated by Strahler (1950; 1956) who compared areas of different terrain using the hypsometric integral and slope gradient distributions. Wood and Snell (1960) performed a quantitative analysis to classify terrain into physiographic regions based on several landform attributes. Gregory and Brown (1966) compared morphological map units with measures of descriptive statistics derived from slope distributions. Speight (1968) set up a parameter base of specifically defined landform attributes to quantify landform elements and landform patterns which were obtained from contour lines; whereas Parry and Beswick (1973) were the first to derive quantitative landform parameters from airphotos. In a later project, Speight (1976) grouped the landform elements in terms of their relevance to geomorphic processes using cluster analysis; similar classifications using multivariate analysis techniques were implemented by Gardiner (1976), Laut and Paine (1982), Carrara (1983), and Pennock *et al.* (1987).

Although, all of the above examples were based on an automated numerical process to analyse or classify landforms, the landform categories were defined by the operator and the terrain measurements were, in most instances, derived manually from maps or airphotos. Evans (1972; 1981) was one of the first to use digital terrain models in a quantitative analysis. He divided the quantitative description of landforms into specific and general geomorphometry. General geomorphometry is defined as the measurement of a continuous rough surface described by attributes of sample points over an area. In contrast, specific geomorphometry describes single landforms by their size, shape and relation to each other and requires a precise definition and delimitation of the landform element (Evans, 1981). Weibel and DeLotto (1988) and Weibel (1989) carried the concept of general and specific geomorphometry even further. In their research, general geomorphometry is related to a general or global pattern recognition whereas specific geomorphometry is related to a linear or local pattern recognition characterized by mathematical equations. General geomorphometry has been used to discriminate between different landforms covering large areas based on moment statistics and correlation (Evans, 1972; 1980), spectral analysis (Pike and Rozema, 1975), and fractal analysis (Mark and Aronson, 1984; Goodchild and Mark, 1987). According to Weibel and Heller (1991), the application of specific geomorphometry is related to the extraction of distinct landform types such as drumlins, ridges or cirques (Evans, 1987) and the delineation of channels and ridges (Douglas, 1986; Band, 1986; Mark, 1984).

While Evans introduced the principle of general and specific geomorphometry to quantitative landform analysis, Pike (1988, p. 494) defined the principle of geometric signature "as a set of measurements that describe topographic form well enough to distinguish geomorphologically disparate landscapes". Pike based the discrimination between hard and soft terrain affected by landslides on such a set of geometric measurements. The definition of geometric signature allows the analogy of landform classification with land cover classification as undertaken in remote sensing analysis (Weibel and DeLotto, 1988). While, conventional classification methods consider attribute characteristics only, several attempts have been made in the past two decades to incorporate spatial characteristics into the classification (Haralick and Shanmugam, 1974; Kettig and Landgrebe, 1976; Pavlidis, 1982; Fu, 1982). The spatial characteristics are of special importance when patterns are classified because unlike elements, which form discrete units, patterns consist of continua. Two different spatial characteristics, context and texture, which are fundamental to the human interpretation of patterns, have been used in image processing and classification. Context refers to the spatial relationship within the surrounding area of a picture element whereas texture describes the spatial distribution of a variable within the surrounding area of a picture element (Haralick *et al.*, 1973; Jensen, 1986). Texture and context information have been used as spatial modifiers in image pre- and post-processing to segment an image into regions of homogeneous texture (Haralick and Shanmugam, 1974; Kettig and Landgrebe, 1976; Landgrebe, 1980; Thomas, 1980; Cross *et al.*, 1988;) and in the classification process itself (Kettig and Landgrebe, 1976; Franklin and Wilson, 1991; 1992; Wharton 1982; Gong and Howarth, 1992; Eyton, 1993). The referenced textural and contextual analysis and classification statistical approach to pattern recognition whereas a structural approach as described in Fu (1982) resembles intuitively more the human recognition process but is more complex to model automatically (Harris, 1980).

In most landform classifications used for land surveys, landform patterns are categorized instead of specifically defined landform elements. As a consequence, the determination of spatial characteristics are of special importance in landform classification (Speight, 1974; Mark, 1979). Mark stated that landform units have to be extracted from digital terrain models according to a set of geomorphologically based patches instead of single elevation points. Some of the above referenced methods which consider the spatial aspect for pattern recognition, have been implemented in semiautomated and automated landform classification in recent years (Weibel and DeLotto, 1988; Weibel, 1989; Chorowicz *et al.*, 1989; Dikau, 1989). Weibel and DeLotto (1988, p.618) defined the process of automated landform classification as follows: "Automated terrain (landform) classification involves the partitioning of an area into homogeneous topographic regions through quantitative interpretation of a digital terrain model". The approach to landform classification implemented in this thesis follows the process described by Weibel and DeLotto. But, instead of applying a statistical textural classifier, as used by Weibel (1989), Weibel and DeLotto (1988), and Pike (1988), a frequency-based contextual classifier is implemented based on a method described by Wharton (1982), and used by Gong and Howarth (1992), and Eyton (1993) in urban land use classification. According to this method, class frequency counts are derived from an area surrounding the grid points and are used as contextual classifiers in a multivariate classification. The use of contextual classifiers has the advantage over textual classifiers that frequency counts contain more spatial information than the statistical measures used in the textual classification.

2.6 Digital Terrain Models

The basis for any landform analysis and classification has traditionally been the topographic map, airphotos or field observations. To facilitate a quantitative landform analysis and classification, the digital elevation model (DEM) was developed to represents the land surface numerically. The DEM consists of elevation values assigned to location coordinates of the land surface and forms the base data set for any further terrain modelling. In a DEM, elevation is represented in the form of regularly or irregularly distributed points. The best known structure, which defines the irregularly distributed points, is the triangulated irregular network or TIN. In a TIN structure, the elevation points are linked together by a straight line to form a contiguous, non-overlapping set of triangular elements (Mark, 1979; Peuker *et al.*; 1976). In a regular data structure, the elevation points are arranged in a grid along rows and columns. In this study, a regular grid data set of fixed density is used. The grid data set has several advantages over an irregular data set including simpler data handling for interactive computing conversions, neighbourhood calculation, and retrieval of data from storage (Peuquet, 1979). Furthermore, DEMs are provided by government agencies, in most instances, in regular grid form only. The disadvantage of a regular raster distribution is the fact that the density of the data points cannot be adjusted to the roughness of the terrain (Weibel and Heller, 1990).

A variety of morphometric parameter can be derived from the DEM. The most commonly used derivatives of DEMs are local relief, slope gradient and azimuth, downslope and across slope curvature, relative radiance and flow path models (Burrough, 1986, Oswald and Raetzsch, 1984; Mark, 1975; 1984; Pike, 1988; Douglas, 1986; Evans, 1980; Weibel and Heller, 1991). Digital terrain models (DTMs) are constructed using one of two approaches; one approach involves the numerical calculation of the terrain parameter at a specific location using finite difference approximation (Tobler, 1970; Eyton, 1991) which is applied in this research. A second approach fits an equation such as a least square polynomial (Evans, 1980; Young, 1978; Zevenbergen and Thorne, 1987) or an exact fitting multiquadric equation (Hardy, 1971; Eyton 1974) to the land surface globally to derive the morphometric parameter analytically. Other analytical techniques which have been applied to describe a land surface as a whole are spectral analysis (Pike and Rozema, 1975; Papo and Gelbmann, 1984), fractal analysis (Mark and Aronson, 1984; Goodchild and Mark, 1987) , trend surface analysis (Clerici, 1980), and kriging (Burgess and Webster, 1980a; 1980b).

Automated techniques used to display DEMs and DTMs are numerous such as contour maps with and without edge enhancement or illumination, continuous or classed grey scale or colour coded maps, hillshading models and perspective views (Peucker, 1980; Oswald and Raetzsch, 1984; Eyton, 1984; 1990; 1991; Burrough, 1986; Judd, 1986; Moellering and Kimerling, 1990). Many of these display and visualization techniques are based on manual cartographic relief representation used to display landform on topographic maps (Imhof, 1982; Keates, 1990).

2.7. Landform Maps

In Canada, landform classifications are in most instances incorporated into soil, geology or ecological maps, whereas, in Europe, individual geomorphological mapping programs are used to map landforms according to morphography (appearance), morphometry (dimension and slope value), morphogenesis (origin) and morphochronology (age) (Verstappen, 1983; Klimaszewski, 1988). The Canadian map, which resembles the geomorphological map the closest, is the map of surficial geology.

Certain differences exist between the representation of landform on European and Canadian maps which are of importance for the application of computer cartography to landform mapping. On European maps, the information about landforms is represented in the form of different information layers. For example, slope gradient, minor forms, curvature, subsurface material and bedrock, present processes, hydrography, and processes and structure are superimposed as separate layers on the German geomorphological map (Barsch and Liedtke, 1980; Barsch and Staeblein, 1989). The layers are differentiated by varying hachures and colours. The Dutch legend developed by the International Training Center (ITC) (Van Zuidam, 1985) is similar to the German legend. The individual information layers can be easily digitized for application in geographic information systems or generated using digital terrain models (Burrough, 1986) because the European systems follow a parametric approach to landform mapping.

On the Canadian map, the individual landform attributes are integrated into one unit. Letter or number notations refer to the individual attribute characteristics, which are defined in a separate legend. The Canadian map is easier to read than the European map because the landform categories are represented as comprehensive units derived using a landscape approach to landform classification. As a result, however, the delineation of the individual attribute units cannot be recovered. Consequently, the delineation of landform polygons representing all parameters will hardly ever coincide with the polygon delineation of an individual information layer, such as surface expression .

Two Canadian mapping schemes, which include landform classifications, are investigated in this research: the Terrain Classification System for British Columbia commonly used by the Geological Survey of Canada (Fulton *et al.*, 1974) and the Canadian System of Soil Classification used by Agriculture Canada (E.C.S.S., 1987a). The Terrain Classification System for British Columbia (Howes and Kenk, 1988), which is based on an earlier published terrain classification (Fulton and Alley., 1974), is often used as guideline for surficial geology mapping in Canada (Fulton *et al.*, 1974) because a national landform classification for use in surficial geology mapping does not exist. The Terrain Classification System for British Columbia emphasizes the complete description of surface material, texture of sediments, surface expression, geologic processes and qualifying processes (Fulton and Alley, 1974; Howes and Kenk, 1988). Landform is specified by surface expression and is concerned with the form and structure of slope elements, and the arrangements of landforms, including relief and drainage patterns. In the recent version of the Terrain Classification System (Howes and Kenk, 1988), the relief modifier is replaced by a slope gradient modifier. In addition, attempts have been made to develop a terminology for surface expression which is free of genetic interpretation. For example, descriptors of surface expression such as *ridged*, *undulating*, or *flat* are used as opposed to *end moraine*, *ground moraine* or *floodplain*.

The landform classification incorporated in the Canadian System of Soil Classification (E.C.S.S., 1987a) is closely linked to the Terrain Classification System for British Columbia. One of the objectives of the Canadian System of Soil Classification is to provide a system which recognizes the landform component in the mapping unit used by soil surveyors. Four components have been recognized for the use in landform classification: genetic material, material modifier, surface expression, and slope. The system allows to map all landforms comprehensively rather than stress prominent features. The system applies to maps at scales of 1:50,000 to 1:500,000. The surface expression of a landform is mapped according to the form consisting of an assemblage of slope elements and patterns of forms.

The definitions of surface expression and slope gradient classes used by the Canadian System of Soil Classification and by the Terrain Classification System are summarized in Table A1.1 in the Appendix. In the table, the different surface expression labels of both systems were correlated according to similar descriptions. Most surface expression labels and descriptions are defined similarly in both systems and should provide the basis for the mapping of compatible landform classifications.

Canada was one of the first countries to produce a computer based land inventory, in which the different data layers in the land system classifications, including landforms, are stored in a geographic information system (Tomlinson *et al.*, 1976; Thie *et al.*, 1979). The Canada Soil Information System (CanSIS) was designed to especially store and manipulate soil inventory data (Dumanski *et al.*, 1975). However, DTMs have not been incorporated in such digital land inventory nor have they been used in landform mapping by soil and geology surveys in Canada because DTMs covering entire provinces have only recently been generated. But applications of DTMs in soil classifications have been reported elsewhere. For example, in the United States, DTMs of slope gradient and azimuth have been used to facilitate premapping of soil units (Klingebiel *et al.*, 1987) and the combination of DTMs with soil premaps provided tabular statistical summaries of soil unit delineations (Horvarth *et al.*, 1987). Furthermore, DTMs have been used for the automated delineation of landform in soil surveys to predict soil drainage and soil moisture regimes (Bork and Rohdenburg, 1986; Bell et al., 1991).

2.8 Summary

In this thesis, landform refers to the morphology of the land surface only. Material and processes are excluded from the classification. Furthermore, landforms are mapped and classified as regions consisting of predefined assemblages of landform elements as defined by the Canadian Ecological Land Classification. Given the spatial aspect of mapping and classifying landform regions, the classification methodology has to be based on attribute as well as locational homogeneity.

The landscape approach and the parametric approach, have been used commonly for mapping and classifying landform regions. The landscape approach groups individual landform elements into comprehensive units of recurring landform patterns based on qualitative classification criteria. The parametric approach classifies landform units on the basis of selected measurable attributes and is referred to as being a quantitative method. The parametric approach has the main advantage over the landscape approach of facilitating the application of numerical techniques and therefore computer technology to landform classification.

For this reason, the parametric approach is applied in this thesis to provide an objective landform classification while, at the same time, an attempt is made to incorporate the comprehensiveness of the landscape approach.

Quantitative analysis of landforms has been carried out since the 1950's. Since the 1970's digital terrain models have been used in landform analysis and classification. Since then, three main postulates have been defined which are relevant for the classification of landform in this thesis: first, the approach is based on the principle of general geomorphometry; second, landforms are defined by geometric signature; and, third, the classification of landform patterns has to incorporate the concept of spatial context into the classification process.

In this thesis, landform categories are analysed and classified according to surface expression and quantitative modifiers of slope gradient and local relief as defined by the Canadian System of Soil Classification and the Terrain Classification System for British Columbia used by the Geological Survey of Canada. The specific soil and geology maps, which are the subject of this research, are described in the following chapter along with the study area and the digital elevation models used to analyse and classify the landform categories.

3. Study Area and Data Sources

Three criteria had to be satisfied for the selection of the study area: first, the presence of landforms of varied relief and different surface expression; second, the existence of land system maps at a scale of 1:50,000 or smaller containing landform classification modifiers; and, third, the availability of Alberta 1:20,000 digital elevation models (DEMs). These criteria were met for an area located in east central Alberta in the northern part of the County of St. Paul. The location is also referred to as the Sand River area and covers the eastern portion of the 1:50,000 topographic map sheet 73L05, as well as the western portion of the map 73L06 within the easting UTM coordinates 451200 to 480250 and northing coordinates 6011400 to 6032500 for zone 12U (Figure 3.1). The area consists of a wide variety of glacially, glacio-fluvially and fluvially formed landform types of low to medium relief. 1:50,000 soil and surficial geology maps which were mapped according to the guidelines of the Canadian System of Soil Classification (E.C.S.S., 1987a) and the Terrain Classification System (Howes and Kenk, 1988), and Alberta 1:20,00 DEMs were available for the area.

3.1 Description of the Study Area

The elevation in the 21 km x 29 km large study area ranges from 525 to 685 meters above sea level. The lowest elevation is associated with the Beaver River in the north which forms the major drainage system in the region flowing eastwards to the Churchill River. The highest elevation is found in the central part of the study area which is referred to as the Lac La Biche Upland (Andriashek and Fenton, 1989; Figure 3.2) or Vincent Upland (Brierley *et al.*, 1990; Figure 3.3). The landscape is characterized by *ridged* to *rolling* glaciofluvially streamlined terrain with a strong NW to SE orientation. The local relief varies from 5 to 15 meters with slope gradients of 7 to 15 percent.

The Garner Upland (Andriashek and Fenton, 1989) or Bunder Upland (Brierley *et al.*, 1990) lies at a slightly lower elevation varying from 610 to 640 meters. The high relief hummocks and knolls form part of a thrust moraine consisting of till of a higher clay content than the medium textured till found on the Vincent Upland. Many lakes such as Bunder and Norberg Lake fill depressions formed by the down-wasting process of the glacier. The local relief ranges from 10

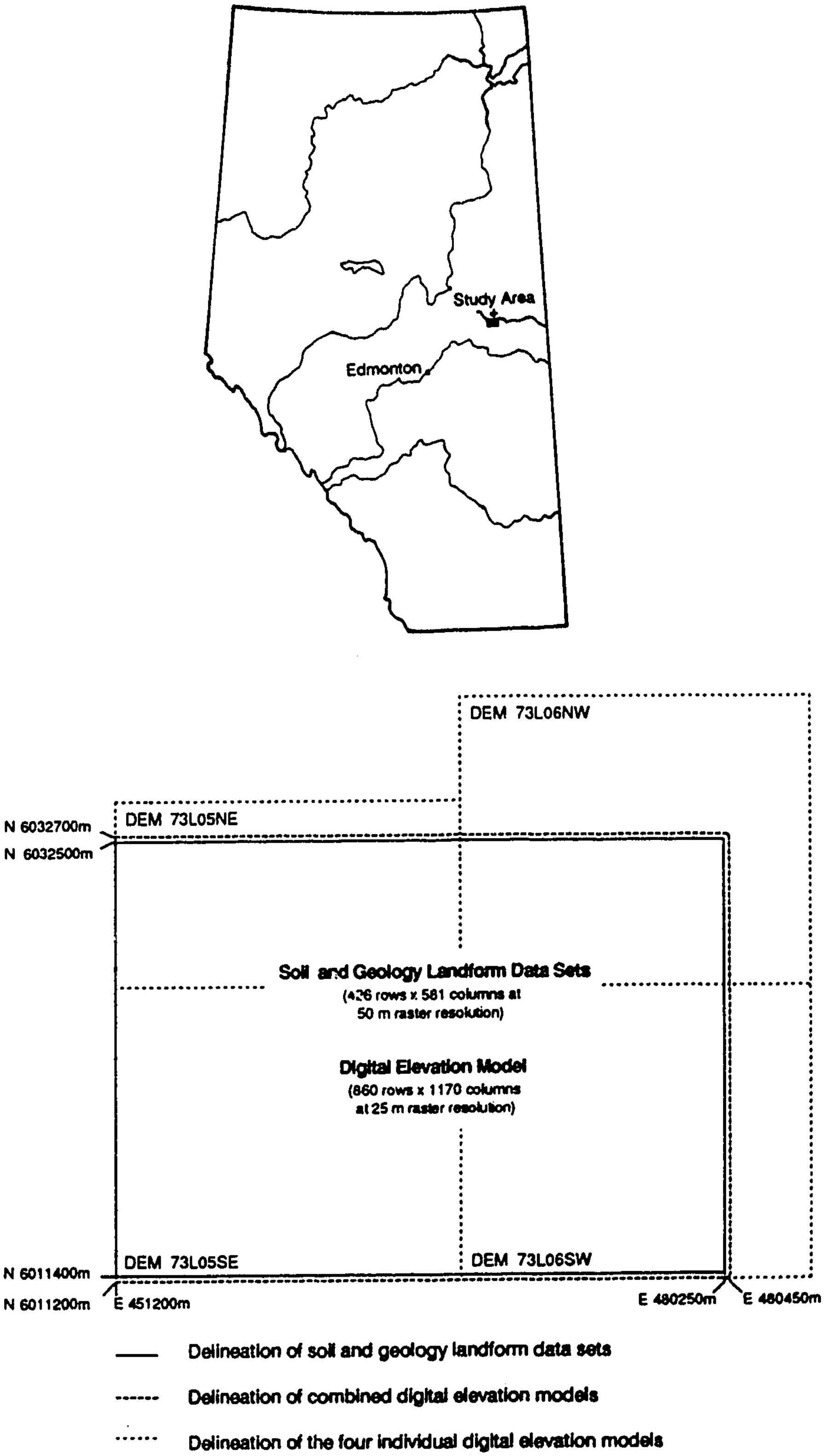


Figure 3.1. Location of study area in Alberta and delineation of digital data sets

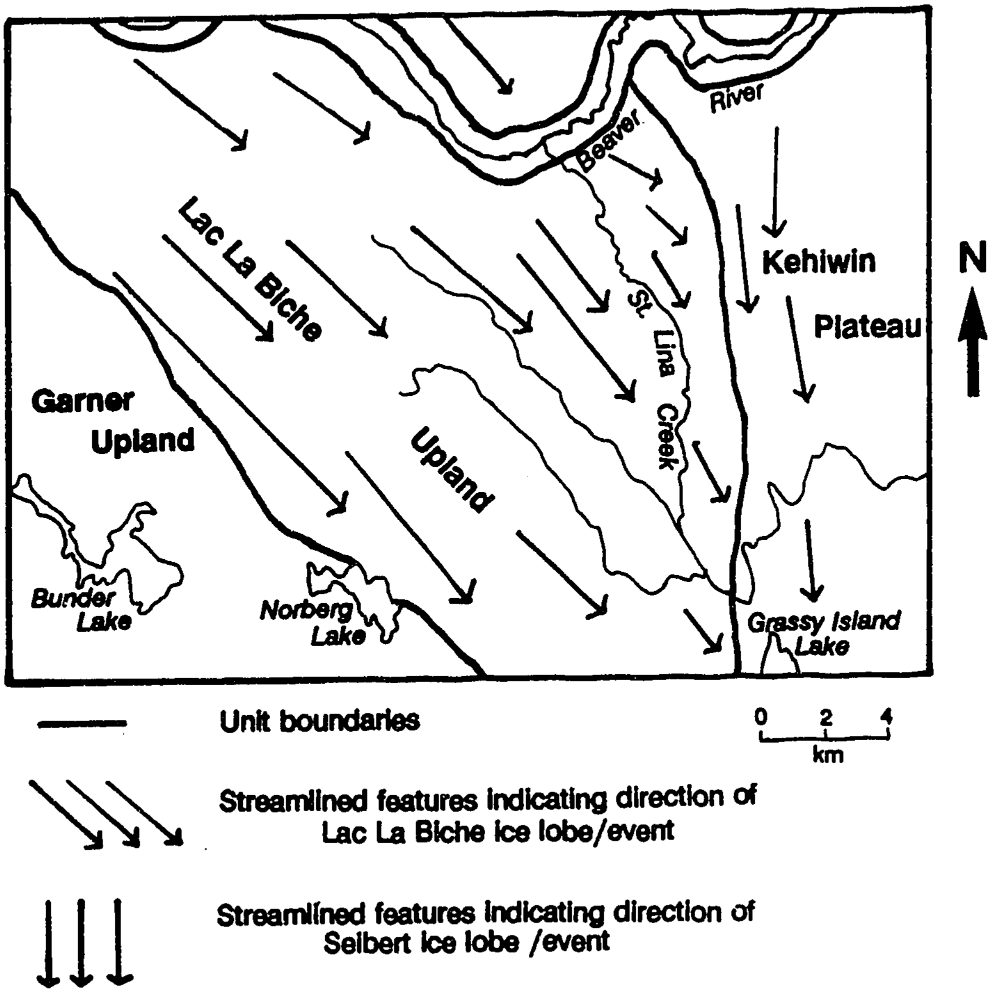


Figure 3.2. Physiographic units and direction of ice lobe/event modified after Andriashek and Fenton (1989)

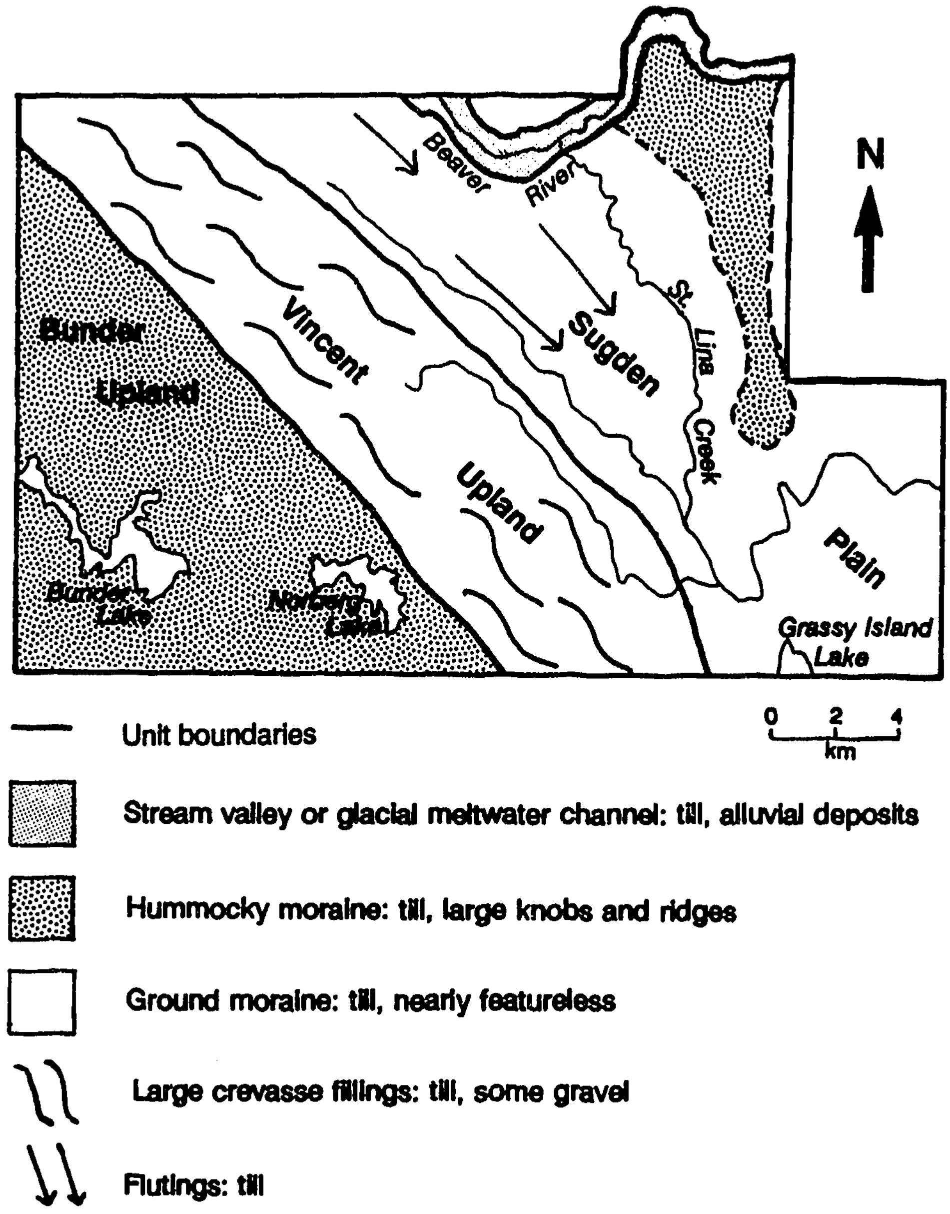


Figure 3.3. Physiographic units and surficial deposits modified after Kocaoglu (1975) and Brierley *et al.* (1990)

to 20 meters and the slope gradient of 10 to 20 percent is higher than anywhere else in the study area except for the steep banks along the Beaver River drainage way.

The Sugden Plain (Brierley *et al.*, 1990) or Kehiwin Plateau (Andriashek and Fenton, 1989) in the east has the lowest relief in the study area of 0.5 to 1 meter and slope gradients of 1 to 3 percent. The landscape is part of a ground moraine and is comprised mainly of *flat* to *smoothly rolling* landforms draped by doughnut-like hummocks. The landforms were formed by erosional and depositional processes. Runoff is collected in large depressions which caused the accumulation of organic material due to poor drainage. The relief is considerably higher to the north of the Sugden Plain south of the meander neck of the Beaver River which is related to a thrust moraine.

The landscape of the study area was formed by glacial, glaciofluvial and fluvial processes as described by Kocaoglu (1975), Jones (1982), Andriashek and Fenton (1989), Brierley *et al.* (1990), and Rains *et al.* (in press). The last glacial events took place during the late Wisconsin glaciation. Two independent theories exist to explain the formation of the glacial, glaciofluvial and fluvial features. According to the first theory, two independent ice lobes, the Seibert lobe, which advanced from the north into the study area, and the Lac La Biche lobe, which advanced from the northwest, are believed to have shaped the glacial and glaciofluvial landforms (Andriashek and Fenton, 1989, Figure 3.2). The region associated with the extent of the Seibert lobe coincides with a ground moraine covering most of the Kehiwin Plateau (Andriashek and Fenton, 1989; Figure 3.2) or Sugden Plain (Brierley *et al.*, 1990; Figure 3.3). Before the Lac La Biche lobe advanced, the Seibert lobe stagnated and the succeeding down-wasting process formed the hummocky area in the southwest associated with the Garner Upland (Andriashek and Fenton, 1989) or Bunder Upland (Brierley *et al.*, 1990). A later advance of the Lac La Biche lobe overrode most of the area in the northwest which had been covered by the Seibert lobe. A thrust moraine was formed at the contact of the Lac La Biche and Seibert lobes extending southwards from the Beaver River meander neck (Figure 3.3). Flutings on the Lac La Biche Upland were created by a 20 km wide ice stream of the Lac La Biche lobe. At the contact to the Seibert lobe the flutings change their orientation from northwest to southeast direction to north to south direction.

The second theory relates the Lac La Biche flutings to a subglacial sheet flow of major flood magnitude (Rains *et al.*, in press). The thrust moraine between

Lac La Biche and Seibert flutings is inferred to be a product of subglacial glaciotectonic processes caused by increased shear stress at the margins of the meltwater sheet. A detailed field investigation related to the second theory has not been carried out in the study area. The landform maps of the study area, however, indicate that the Seibert and Lac La Biche fluting fields confluence in the south of the area. This observation does not support the theory that the Seibert flutings were overridden by the Lac La Biche flutings. On the contrary, the observation indicates that the two fluting fields were formed at the same time (Shaw, personal communication).

3.2 Landform Category Extraction from the Sand River Surficial Geology Map

A published surficial geology map at a scale 1:250,000 and a field copy map at a scale of 1:50,000 of the Sand River area were obtained from the Alberta Research Council (Fenton and Andriashek, 1983). The surficial geology is described in an open legend according to composition, genetic class, genetic modifier, morphology and relief. Only the morphological and relief modifiers, which are directly related to the form, are considered in this research.

The term "morphology", as used on the surficial geology map, is identical with the morphographic modifier used in this research to describe surface expression, such as *hummocky* or *ridged*. On the geology map "morphology" refers to both the shape of the landform within the map unit and the continuity of a particular genetic category (Andriashek and Fenton, 1989; Table A1.3). The morphometric modifier represented by local relief on the surficial geology map refers to the average difference in elevation between hills or ridges and adjacent depressions within a particular map unit (Andriashek and Fenton, 1989; Table A1.4). Polygons differentiated by relief and morphographic modifiers were digitized and transformed from a vector into a raster data set of 50 m grid resolution using the programs GEODIGIT and VEC2RAS (Department of Geography, 1989). The grid resolution differs between the geology and soil data sets and the digital elevation model caused by differing map scales. The geology and soil maps are presented at a 1:50,000 scale which does not provide the detail to produce raster data sets of 25 m grid resolution used by the 1:20,000 Alberta elevation models. All landform maps derived from digital terrain models, soil or geology data sets are mapped at a scale 1:150,000 in this thesis.

Figure 3.4. Surficial geology landform map, modified after Fenton and Andriashek (1983)

The landform categories of the geology landform map were colour coded as presented in Figure 3.4 and listed in Table A1.6 in the Appendix. A different hue was assigned to each category of surface expression. The hue varies in brightness according to the local relief modifier and the brightness increases with an increase in local relief. Consequently, the landform units can be distinguished not only according to varying surface expression but also according to different local relief classes.

3.3 Landform Category Extraction from the County of St. Paul Soil Survey Map

Two soil maps exist of the area. One was published in 1975 at a scale 1:126,720 as part of the western sheet of the Sand River Area Soil Survey (Kocaoglu, 1975). The second one covers the County of St. Paul at a scale 1:50,000 (Brierley *et al.*, 1990). In this research, the County of St.Paul soil map was preferred over the Sand River soil map because the latter delineates landform types only in a very general way. In contrast, the landform classification used for the County of St.Paul soil map distinguishes the landforms of each soil polygon according to surface expression (Table A1.3) and slope gradient (Table A1.4) as outlined in the Canadian System of Soil Classification (E.C.S.S., 1987a). These modifiers are incorporated in a closed legend. The slope gradient classes, representing the morphometric component, and the surface expression categories, representing the morphographic component of the landforms, were derived by airphoto interpretation and field survey (Brierley *et al.*, 1990).

For this research, polygons containing slope gradient and surface expression were digitized from the County of St.Paul 1:50,000 soil survey map and converted from a vector to raster data set of 50 m grid resolution using the programs GEODIGIT and VEC2RAS (Department of Geography, 1989). A colour scheme (Table A1.6) similar to the surficial geology map (Figure 3.4) was assigned to the landform categories of the soil survey map (Figure 3.5); the brightness of the hue increases with an increase in slope gradient. The soil survey map does not extend as far north and east as the surficial geology map and the DEMs because the limit of the soil map coincides with the county boundary of St. Paul (Figure 3.2 and 3.3).

Figure 3.5. Soil survey landform map, modified after Brierley *et al.* (1990)

3.4 Alberta 1:20,000 Digital Elevation Model

The Alberta 1:20,000 Digital Topographical Data Base (DTDB) project was initiated by Alberta Forestry, Lands and Wildlife in 1984 to provide a digital database for use by government agencies and private sector companies (Toomey, 1986; Toomey, 1988; Johnson, 1988). Part of the project involved the generation of Alberta 1:20,000 DEMs. For the DEMs, elevation data of a variable grid mesh were sampled every 1.6 mm to 2.0 mm from 1:60,000 airphotos using stereo compilation. Breaklines and spot heights were added. The elevation data were then transformed to a 25 meter grid using the surfacing program SCOP (Stuttgart Computer Program; Koestli and Wild, 1984). The accuracy of the data points varies from 3 to 10 meters at a 90 percent vertical accuracy level and 5 to 15 meters at a 90 percent horizontal accuracy level (Alberta Bureau of Surveying and Mapping and Resource Evaluation and Planning Division, 1985).

Four DEMs were provided by the Land Information Services Division of Alberta Forestry, Lands and Wildlife (1985) corresponding to topographic map sheets 73105 and 73106 as presented in Figure 3.1. The DEMs consist of elevation data given in vector format as X, Y, Z coordinates, representing spot heights, breaklines and a regular 25 meter grid of elevation points. The points corresponding with the regular grid were extracted and placed into a raster data set. The DEMs were then smoothed once using a low-pass filter to diminish the noise. The noise consisted mostly of the grid sampling pattern which in some instances is still visible on the curvature maps. Finally, the four DEMs were registered and combined to form a new data set coincident with the soil and geology map (Figure 3.1).

3.5 Digital Terrain Models

From the combined DEM a wide variety of digital terrain models (DTMs) can be derived. The list of models used in various studies is extensive and includes variables such as altitude, relief, slope, fine texture, hypsometry (elevation skewness), slope curvature in profile, slope curvature in plan, slope direction (azimuth), topographic grain, parallelism in plan, proportion of fine and coarse scale slopes, drainage topology, cluster versus random versus even spacing of features (wavelength) (Strahler, 1950; 1956; Wood and Snell, 1960; Parry and Beswick, 1973; Speight, 1976; Evans, 1972; Pike, 1988; Dikau, 1989; Weibel, 1989).

1989). Variables used in studies of general geomorphometry are associated with five main variable groups: elevation, slope, azimuth, curvature and texture (Evans, 1980; Franklin, 1987; Pike, 1988; Weibel and DeLotto, 1988; Weibel, 1989). Regression analysis has also proven that those variables are less correlated and are complementary (Mark, 1975; Evans, 1980).

In addition to the above variable list, Mark (1975) described texture as representing the shortest wavelength and grain representing the longest wavelength. Both variables, texture and grain, define the horizontal variation of terrain whereas relief describes the vertical variation of terrain (Evans, 1972; Mark, 1975). In contrast, Franklin (1987) described relief as a surface variable based on texture measures of entropy and angular second moment. Other measures which have been used to characterize terrain roughness or texture are the variance power spectrum (Pike and Rozema, 1975) and fractal dimension (Mark and Aronson, 1984; Goodchild and Mark, 1987). According to Weibel (1989), the use of the latter measurements in landform classification is limited, a point, which will be discussed in detail in chapter 5 and 7. Morphometric variables of local relief, slope gradient, azimuth, and curvature were selected for the display, analysis and classification of landforms in this study.

Local relief describes the vertical dimension in terrain analysis and represents the difference between the highest and lowest elevation occurring within a finite area (Mark, 1975). Difficulties arise in defining the area over which the elevation range is measured, these will be discussed further in chapter 5. Relief was first used by Partsch (1911) as a measure to describe relief energy and has been selected as variable in this study because it is used as a modifier on the surficial geology map.

Slope gradient is one of the key modifiers used in ecological, forestry, earth science, engineering and agricultural applications because slope gradient controls the gravitational forces (Strahler, 1956) for runoff, erosion, mass movement and trafficability. Slope gradient is the first derivative of elevation and presents the rate of change of elevation over a distance (Evans, 1980; Eyton, 1991). Slope gradient is calculated as the maximum slope of a plane tangent to the surface at a point (Eyton, 1991) and is measured in degrees or percent slope.

Slope azimuth represents change in elevation in the downslope direction (Eyton, 1991; Evans, 1980) and is a circular distribution. In geology, azimuth provides an indicator for trends of geologic formations and lineaments. With increasing gradient, azimuth influences microclimate, soil moisture, temperature, and vegetation characteristics. However, in the low relief terrain, as present in the study area, flat areas are portrayed as having the same variations in orientation as areas of high relief although the change in azimuth does not have any ecological implications. As a result, the slope azimuth distributions support only the statistical analysis in this research, whereas the slope-azimuth pattern variation of the study area is portrayed in the form of hillshaded models which are widely used to display landform patterns (Moellering and Kimerling, 1990; Eyton, 1991; Johnson, 1988; Horn, 1982; Judd, 1986).

Curvature is a measure of rate of change of slope and affects the divergence and convergence, and the acceleration and deceleration of flow (Eyton, 1991; Zevenbergen and Thorne, 1987; Evans, 1980; Young, 1972; Elghazali and Hassan, 1986). Curvature influences the infiltration capacity of water into soils which in turn influences soil development. Curvature is the second derivative of elevation and represents change of slope over distance (Evans, 1980; Zevenbergen and Thorne, 1987; Eyton, 1991). Evans (1980), and Zevenbergen and Thorne (1987) defined profile curvature as the change of slope gradient and plan curvature as the change of slope aspect which according to Zevenbergen and Thorne is derived transverse to the direction of slope gradient. Directional downslope and across slope curvature, as defined by Eyton (1991), is equivalent to profile and plan curvature but differs from Zevenbergen and Thorne's approach in the way curvature is calculated. Zevenbergen and Thorne base the calculation of curvature on a polynomial equation whereas Eyton uses a finite difference approximation to measure curvature. The directional curvature value is signed and scaled. Negative curvature represents concave landforms, positive curvature convex forms. Evans (1980) and Eyton (1991) argued that across slope or plan curvature portray ridges and channels better than downslope or profile curvature which portrays too much noise. In this study, however, the reverse observation was made. Consequently, only downslope curvature is used to measure curvature.

The DTMs of local relief, slope gradient, slope azimuth, and downslope curvature were derived from the DEM using finite difference approximation for a convolved 3x3 neighbourhood (Eyton, 1991). The method of finite differences differs from second degree polynomials used by Evans (1980) and modified by Zevenbergen and Thorne (1987) in that the finite difference approximation produces sharper breaks because a value is estimated at a specific location derived from differences between two points. The method of second degree polynomial uses the method of least squares which approximates a surface by fitting a second degree polynomial to the entire neighbourhood providing smoother results. The equations for deriving finite difference approximations of slope and curvature are described in detail by Eyton (1991). The programs used to derive the DTMs and maps are part of a display and analysis program package called TERRA FIRMA (Eyton, 1992).

3.6 Summary

The study area is located in the northern part of the County of St. Paul in east central Alberta and consists of landforms of varying surface expression and relief. The landscape was formed by glacial, glaciofluvial and fluvial processes. Three data sets describing the study area were acquired: a surficial geology map (Fenton and Andriashek, 1983), a soil survey map (Brierley *et al.*, 1990) and Alberta 1:20,000 DEMs (Land Information Services Division, 1985). Landform categories, characterized by surface expression and local relief or slope gradient, were digitized from the surficial geology and soil survey map. DTMs of local relief, slope gradient, azimuth and downslope curvature were derived from the combined DEM prior to the display, analysis and classification of landforms, which will be the focus of the following chapters.

4. Interpretation of Landform from Digital Terrain Model Maps

Landform categories, as delineated on surficial geology and soil maps, have been traditionally interpreted from airphotos, topographic maps, and field observations. In this research, the conventional airphotos and topographic maps are replaced by digital terrain model (DTM) maps, while retaining the technique of manual image interpretation. The use of DTM maps in image interpretation has the advantage over topographic maps and airphotos in permitting a quantitative representation of landform. Furthermore, the use of DTMs allows the application of automated display techniques which provide a fast and flexible adjustment of landform presentation according to the objectives of the mapping project.

A detailed evaluation of the use of Alberta 1:20,000 DTMs in terrain analysis has been presented by Johnson (1988, p.56) who concluded that "... this study has not provided a terrain analysis *per se* but rather, has provided an example of the type of quantitative terrain descriptions which may be generated objectively and consistently and then integrated into any detailed terrain analysis or evaluation system". The landform interpretation described in this chapter builds on Johnson's research. But, instead of providing a general terrain analysis, this study focuses on the specific interpretation of landform categories as mapped on Canadian surficial geology and soil maps. On the Canadian soil and surficial geology maps, landform categories have been differentiated according to surface expressions and morphometric modifiers. Surface expression describes the form and pattern of a landform, whereas morphometric modifiers categorize the landform categories quantitatively. The delineation of homogeneous units of morphometric modifiers will be addressed in the next chapter. The objective of the current chapter is the visual interpretation of surface expression as described for landform mapping by the Canadian System of Soil Classification (E.C.S.S., 1987a) and the Terrain Classification System (Howes and Kenk, 1988) (Table A1.1), and, more specifically, for landform mapping in the study area by the Sand River surficial geology survey (Andriashek and Fenton, 1989) and the County of St.Paul soil survey (Brierley *et al.*, 1990) (Table A1.3) from digital terrain models.

This chapter is divided into the following three parts: first, automated techniques used to display digital elevation models (DEMs) and DTMs in the form of classed or continuous grey scale maps are described; second, the suitability of

DTMs for the interpretation of surface expression is investigated; and, finally, landform categories of surface expression are interpreted and mapped from DEMs and DTMs of local relief, slope gradient, curvature and relative radiance and are visually compared with the existing soil and surficial geology landform maps of the study area.

4.1 Display of DTMs

To facilitate the interpretation of landform patterns from DTMs, mapping techniques used to display and enhance the DEM and DTMs have to be selected carefully. The appropriate technique is dependent upon user requirement, accuracy, aesthetically pleasing presentation, available technology, and cost of production. The transformation of the three-dimensional landform to a two-dimensional map, while at the same time preserving the three-dimensional perception, is the most difficult task in any landform presentation. Perspective views, contour mapping with and without edge enhancement or illumination, colour coding and hillshading are some of the visualization methods which have been used to maintain the depth perception (Peucker, 1980; Oswald and Raetzsch, 1984; Eyton, 1984; 1990; Burrough, 1986; Kraak, 1989; McLaren and Kennie, 1989; Weibel and Heller, 1991).

In this research, hillshaded models were chosen for the three dimensional display of landform patterns, because they provide a planimetrically correct presentation of the earth surface. Depth perception is achieved through shading as described in detail by Horn (1982). Computer methods of generating hillshaded models have been presented, for example, by Judd (1986), Moellering and Kimerling (1990), and Eyton (1991). In this thesis, a relative radiance model was generated from the slope gradient and azimuth model according to an equation for Lambertian reflection developed by Donker and Meijering (1977) and used by Eyton (1991). A solar elevation of 25 degrees and a solar azimuth of 45 degrees were selected to portray the low relief NW to SE oriented flutings in the study area optimally.

The DEM and DTMs of local relief, slope gradient, relative radiance and downslope curvature were displayed as continuous or classed grey scale maps. The generation of grey scale maps has been described by Oswald and Raetzsch (1984), Jenson (1986), Johnson (1988) and Eyton (1991). Advantages and disadvantages of the use of continuous versus classed grey scale maps have been discussed in detail by Tobler (1973) and Dobson (1973). The positions presented in these two papers are relevant for the selection of the appropriate display type which differs for the individual DTM and research objective. Tobler (1973) stated that classed maps lose accuracy by introducing a quantization error due to classification whereas Dobson (1973) argued that the ability of the map user to discriminate between classed values increases with a decrease in the number of classed values and an increase in the number of homogeneous regions. Monmonnier (1977) and Muehrke (1972) supported Dobson's thesis by stating that the use of classed values contribute to the readability and generalization of the map.

Classed maps are very suitable for the delineation of quantitative morphometric parameters such as local relief, slope gradient and downslope curvature because the individual values can be differentiated more unambiguously on a classed grey scale map than on a continuous grey scale map. One of the main discussions, however, in producing classed maps is about the selection of appropriate class limits. Evans (1976) and Burrough (1986) preferred a classification based on standard deviation units whereas Johnson (1988) stated that the selection of class limits should be based on the availability of published classification schemes and the purpose of the map. Since the landform classification in this study is based on the County of St.Paul soil survey and the Sand River surficial geology survey, the DTMs of local relief and slope gradient are classed according to the classification schemes used in these surveys (Table A1.4, Figure 4.3 and 4.4). A classification scheme for downslope curvature is not provided by the surficial geology or the soil surveys because downslope curvature is not used as a morphometric modifier. As a consequence, downslope curvature is portrayed in this thesis according to Young's (1972) curvature classification scheme (Table A1.5, Figure 4.5)

Elevation displayed in form of a classed grey scale map with contour overlay is shown in Figure 4.1. The selection of the contour interval and the class limits for this map is critical. The contour interval has to be small enough to show detail without merging the contour lines and the class limits have to be selected so that information is displayed in a distinguishable number of grey tones (Eyton, 1984). Since the elevation range in the study area amounts to 160 meters, a contour interval of 15 meters was selected in order not to exceed eleven grey tones distinguishable to the human eye (Jenks and Know, 1961). However, at the lower level of the elevation range, larger contour spacing of 20 meters and 25 meters were used to avoid merging of contour lines along the steep banks of the Beaver River. Elevation higher than 675 meters were of very low frequency and were not separated into an extra elevation class (Figure 4.1).

The generation of classed maps is not useful for perceiving landform patterns from hillshaded model maps because the classed display does not provide enough detail. Consequently, the relative radiance model was displayed as a continuous grey scale hillshaded model (Eyton, 1991). The upper and lower 2.5 percent of the distribution were clipped to enhance the contrast of the model.

The brightness of the grey tones on the grey scale maps is an indication of steepness and orientation of landforms. On the hillshaded model, an increase of slope gradient is indicated by increasing brightness for slopes pointing to the source of illumination and decreasing brightness for slopes facing away from the source of illumination (Figure 4.2). On the elevation (Figure 4.1), local relief (Figure 4.3), and slope gradient maps (Figure 4.4), an increase in brightness correlates with an increase in class number. On the curvature map (Figure 4.5), dark areas refer to concave, grey areas to straight, and light areas to convex slopes.

4.2 Suitability of DTM Maps for Landform Interpretation

Landform categories are analysed from DTM maps according to the same principles described for airphoto interpretation (Way, 1973; Verstappen, 1977; Van Zuidam; 1986; Lillesand and Kiefer, 1987). The analyst uses his expertise and knowledge of the area to interpret visual elements from the DTM maps according to shape, size, site, tone, texture, and pattern. Surface expression, as interpreted in this study, is defined by the pattern of these visual landform elements and includes the study of topographic form, drainage pattern, landform boundaries and impression of relief energy and slope steepness.

The ability to recognize different visual pattern elements varies from DEM/DTM to DEM/DTM. DEMs (Figure 4.1) are used to provide a general overview of altitude differences and to delineate the physiographic boundaries within the study area. Detailed landform patterns, however, cannot be discerned from DEMs because the selected contour interval of 15 meters is regarded as too large to depict any specific landform such as hummocks or flutings. These landforms consist generally of a relief of less than 10 meters. The contour intervals and class limits cannot be changed because they are dependant on the range of elevation in

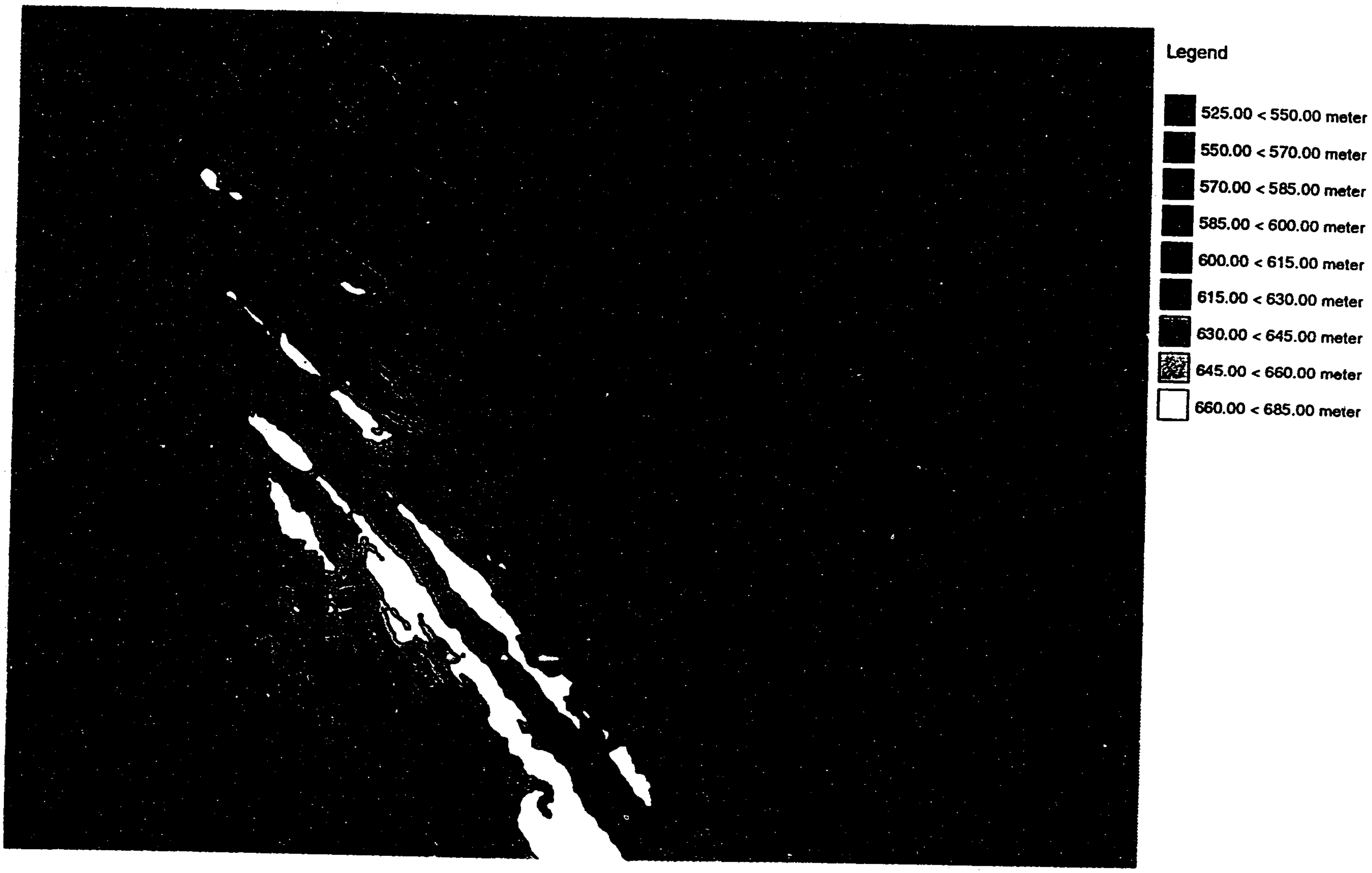


Figure 4.1. Classed elevation model with contour overlay

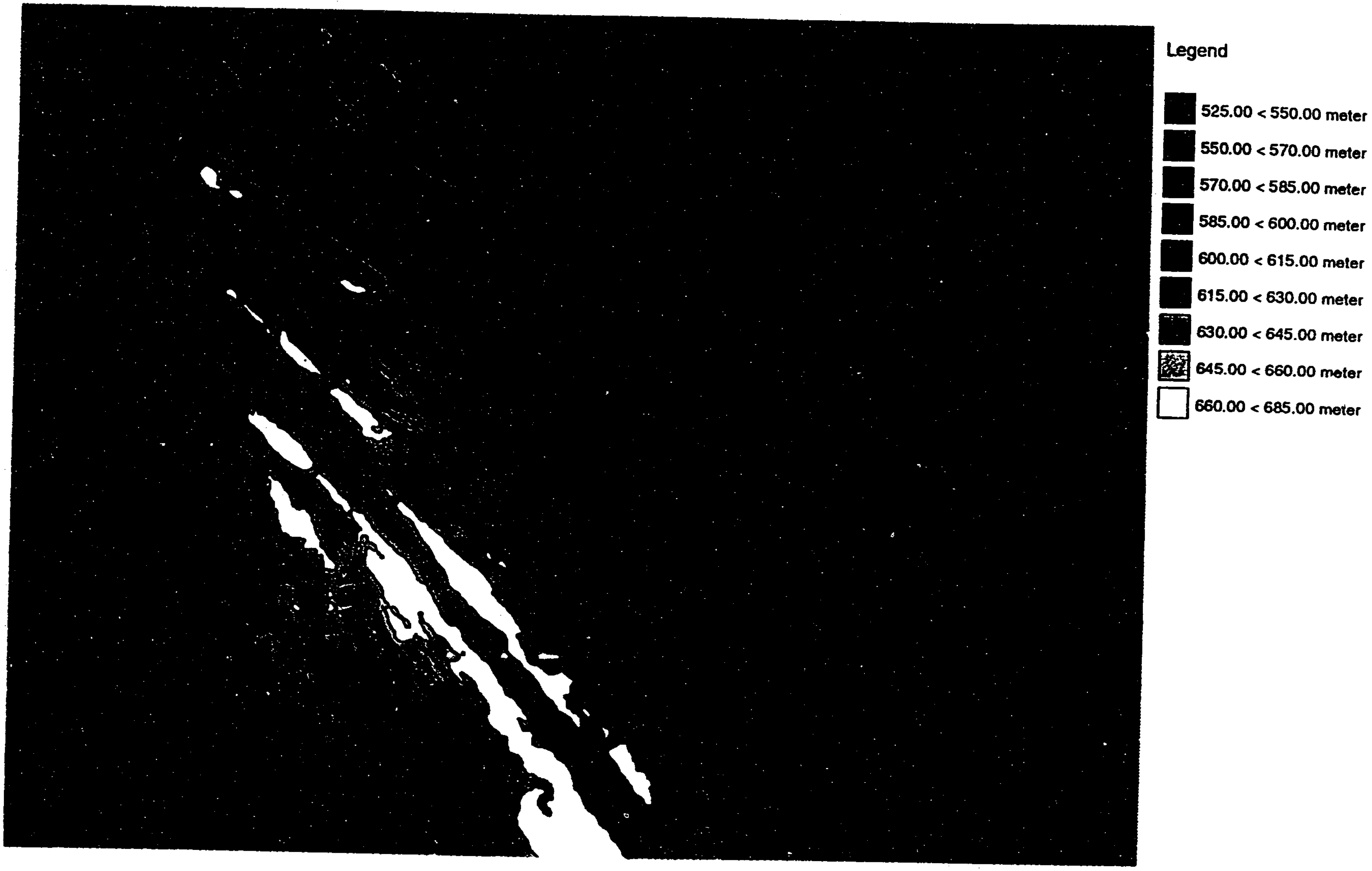


Figure 4.1. Classed elevation model with contour overlay

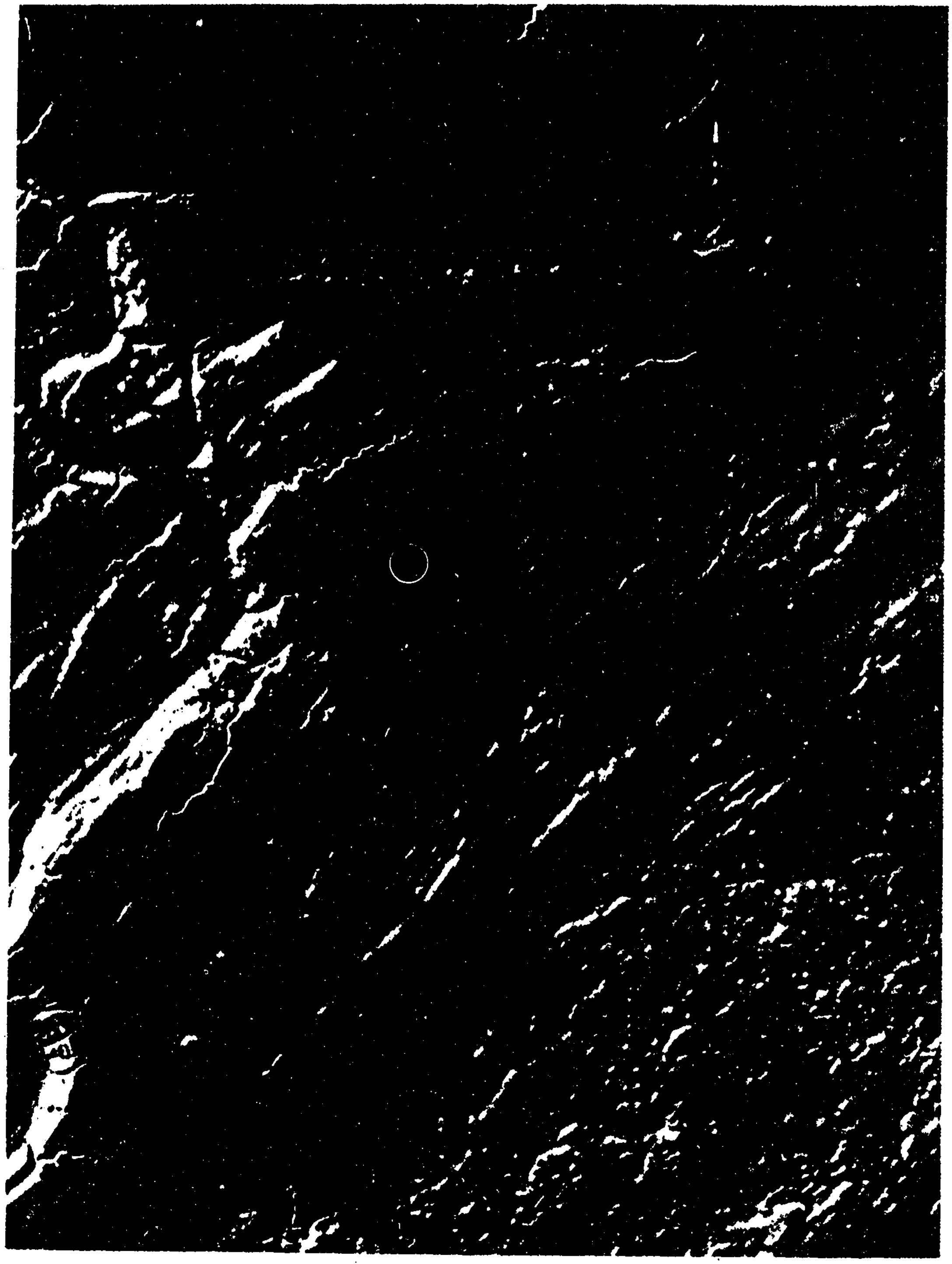


Figure 4.2. Hillshaded model with solar elevation of 25 degrees and solar azimuth of 45 degrees

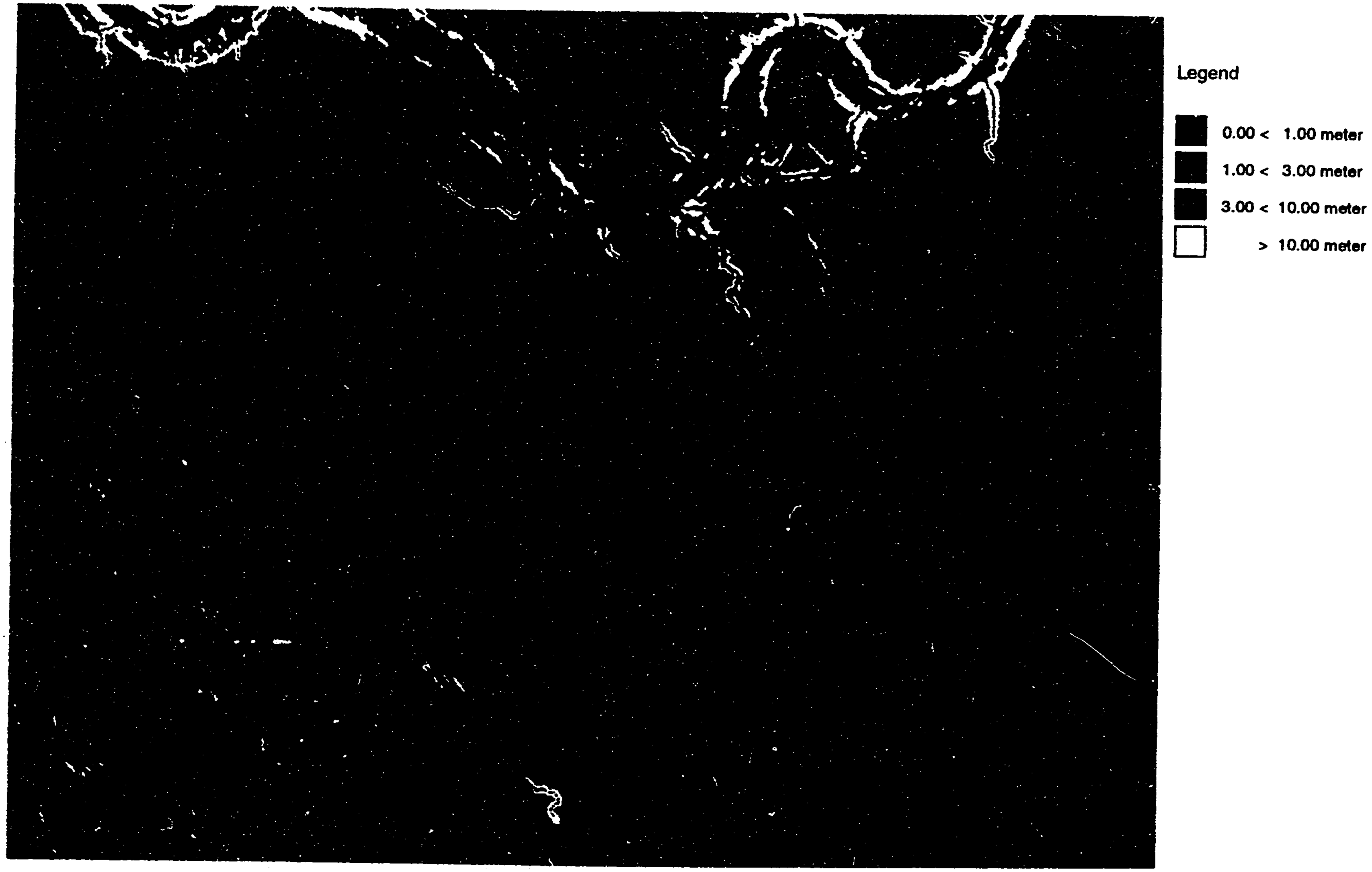


Figure 4.3. Classed local relief model, range derived for a convolved 3x3 neighbourhood

Figure 4.4. Classed slope gradient model

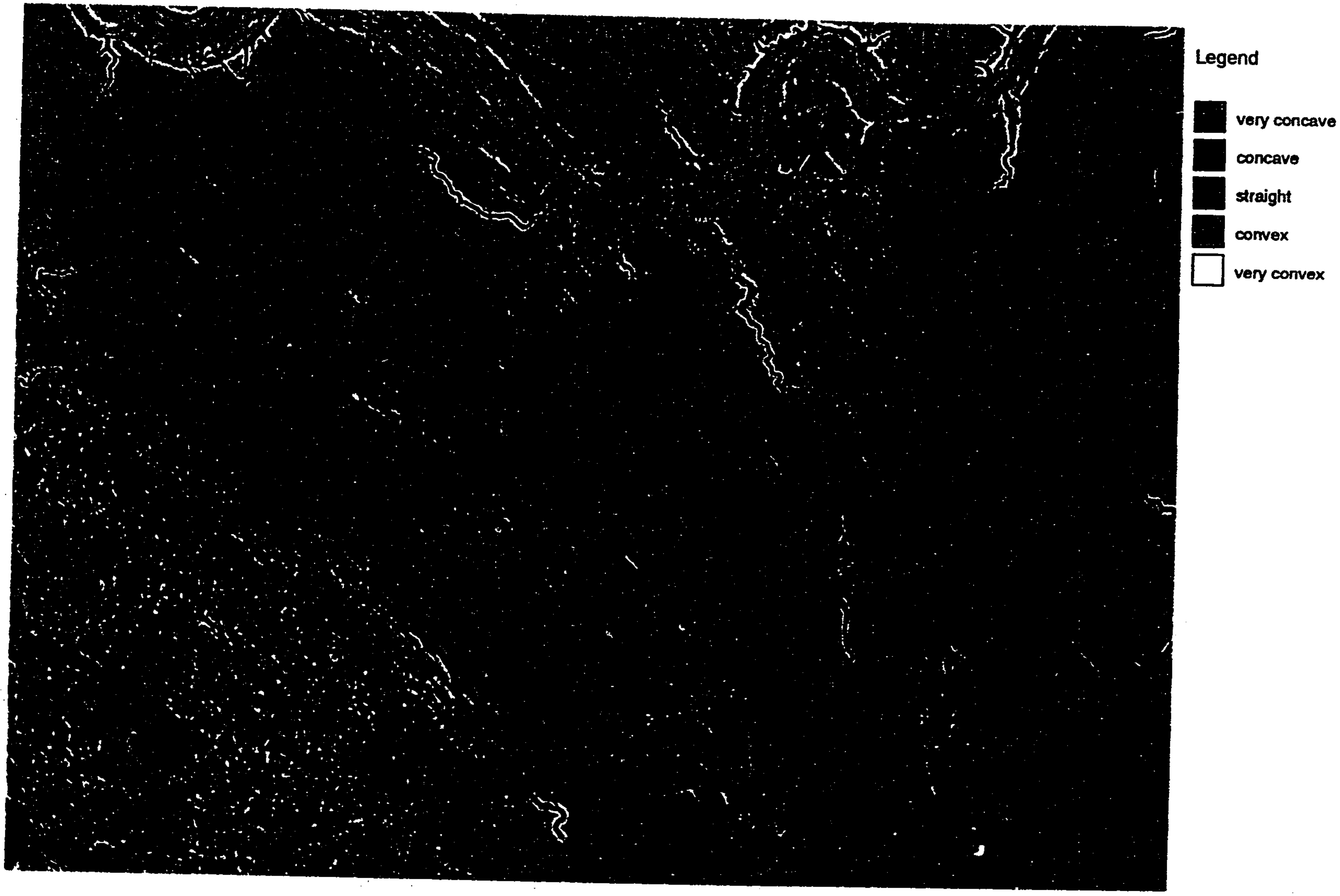


Figure 4.5. Classed downslope curvature model

the study area and the number of classes. To assess elevation differences within different landform units, local relief models are used.

Hillshaded models (Figure 4.2) provide the most important data source for the interpretation of topographic form, landform pattern, and geomorphic structures (Pike and Thelin, 1989; Onorati *et al.*, 1992) because of their close resemblance with airphotos in terms of a realistic impression of relief. In some instances, the hillshaded model is superior to airphotos because vegetation cover and shadow casting does not affect the model (Burrough, 1986) and detail and fidelity can be enhanced by the choice of the solar azimuth and solar elevation (Pike and Thelin, 1989). Furthermore, the interpretation of hillshaded models does not rely on the need to see in three dimensions.

Maps of local relief (Figure 4.3), slope gradient (Figure 4.4) and curvature (Figure 4.5) contribute to the interpretation of landform pattern and add a quantitative dimension to the otherwise qualitative landform interpretation. However, local relief maps derived for a convolved 3x3 neighbourhood, as presented in this chapter, portray a content similar to slope gradient maps. The determination of the finite area, for which the elevation range is measured, is decisive for the derivation of local relief. The neighbourhood size of 3x3 grid cells was too small to determine local relief appropriately. The determination of the optimal finite area will be the focus of the next chapter. Slope gradient and azimuth models have been found to be useful for the delineation of landform units in soil surveys (Klingebiel *et al.*, 1987; Bell *et al.*, 1990). For the purpose of visual interpretation, it is not required to present azimuth on a separate map because change in azimuth is portrayed on the hillshaded model.

Maps of curvature distributions have a second, more important function in landform mapping than solely adding a quantitative aspect to landform interpretation. Curvature is well suited to delineate drainage lines which are of significance in soil and surficial geology surveys (Speight, 1974; Pennock *et al.*, 1987) because curvature portrays convexity and concavity and depicts ridges and channels. Frequently, flow path maps have been used to depict drainage lines (Douglas, 1987; Mark, 1984). Johnson (1988) concluded and a test by the author confirmed that flow path models represent too many insignificant channels of which many may be omitted because they are related to noise.

4.3 Comparison of a Landform Map Interpreted from DTMs with Surficial Geology and Soil Landform Maps

The four main physiographic regions, which were described in chapter 3, can also be differentiated from the DEM and DTMs. A region comprised of almost featureless *flat* to *undulating* landforms in the east is separated by a *hummocky* to *rolling* thrust moraine from a second region consisting of *rolling* to *ridged* landforms in the central part of the study area. A third region consisting of *hummocky* terrain is located in the southwest, and, finally, the Beaver River drainage way in the north forms the fourth region. Each physiographic region is associated with a set of more specifically defined landform categories mapped according to the definition of surface expression by the E.C.S.S. (1987a) and Howes and Kenk (1988) (Table A1.1), and more specifically according to the County of St. Paul soil survey (Brierley *et al.*, 1990) and the Sand River surficial geology survey (Andriashek and Fenton, 1989) (Table A 1.3). The landform units interpreted from the DTMs (Figure 4.1 to 4.5) are delineated on a DTM landform map (transparency) attached in a folder at the back of the thesis. This landform map can be laid over any of the maps produced from the DTMs, or the soil or surficial geology landform maps of the study area. The correspondence of the landform categories interpreted from the DTM maps with landform categories of the soil and surficial geology maps were qualitatively assessed and are summarized in Table 4.1.

The landform category *level*, as delineated on the DTM landform map (transparency), is characterized by an absolutely flat surface of less than 1 meter relief and 2 percent slope gradient and incorporates lakes differentiated in a separate category on the soil and surficial geology landform maps. The lakes can only be differentiated within areas of more pronounced terrain, such as Bunder and Norberg Lake within *hummocky* landforms in the southwestern part of the study area, whereas Grassy Island Lake in the southeast (Figure 3.2 and 3.3) blends in with the surrounding undulating landforms. On the curvature map, some pits and lines show up on the lake surfaces of B[illegible] Norberg Lake due to errors associated with the SCOP program surfaci[illegible]ms (Koestli and Wild, 1984). Other areas, also labelled as *level*, [illegible] to poorly drained depressions delineated as *flat* on the surficial geology map and *level(0-2%)* on the soil map. Those depressions are either associated with organic material, gleysolic, or peaty soils, or are occupied by small lakes. The extent of these units cannot be delineated

Table 4.1. Correspondence of DTM Landform Categories with Landform Categories of the County of St.Paul Soil Classification and Sand River Surficial Geology Classification

Landform Categories		
DTM	soil survey	surficial geology
level	lake, level(0-2%) level(0-10%)	lake, flat
undulating	undulating	flat-hummocky,flat-rolling, rolling(>10m) hummocky-rolling(1-3m)
rolling	undulating	rolling(<10m), hummocky-rolling(1-10m)
hummocky-rolling (medium relief)	hummocky(5-9%) hummocky-ridged(5-9%)	hummocky-rolling(1-10m) ridged-rolling(3-10m)
hummocky-rolling (high relief)	hummocky(>9%)	hummocky-rolling(>3m), rolling(1-3m), rolling(>3m)
ridged	hummocky-ridged(9-15%)	hummocky-rolling(1-10m)
hummocky-ridged	hummocky	hummocky-rolling(1-10m), hummocky-ridged(>3m)
hummocky	hummocky(>9%) hummocky-inclined	hummocky(>3m)
dissected	dissected, level(0-10%)	varied, terraced

on the DTM maps because the change of slope at the margins of these depressions is too small to be portrayed on any of the DTM maps. However, drainage lines visible on the curvature model, which vanish in these depression, can be used as an indicator of their existence and location.

Undulating categories represent wavelike patterned landforms consisting of a series of gentle slopes (E.C.S.S., 1987a; Howes and Kenk, 1988; Table A 1.1). On the surficial geology map, however, such a category does not exist and is labelled as *flat-rolling, flat-hummocky, rolling* of less than 10 meters relief or *hummocky-rolling(1-3m). Undulating* units, delineated on the DTM landform map (transparency), cover the eastern part of the study area, smaller areas are located in the northwestern part of the study area and in between *rolling, hummocky-rolling* and *hummocky-ridged* units. In some instances, these units contain the poorly drained depression described above. Parallel convex and concave lines, which represent the grid sampling pattern of the elevation data, appear on the curvature map within *undulating* units, especially in the eastern part of the study area.

On the DTM landform map (transparency), *rolling* landforms are differentiated from *undulating* landforms by a more pronounced relief, more elongated shape and parallel to subparallel arrangement as described in Table A1.1. Landform units classified as *rolling* on the DTM landform map (transparency) are often associated with *undulating* units on the soil survey map because the landform category *rolling* is not considered in the County of St. Paul soil landform classification (Brierley *et al.*, 1990). For example, a *rolling* unit is delineated on the DTM landform map (transparency) in the central part of the study area south of the Beaver River and consists of streamlined parallel to subparallel features, such as flutings, which are easily distinguishable especially on the hillshaded model. The most prominent fluting runs from northwest to southeast indicating the direction of the Lac La Biche ice lobe/event. On the curvature map, the fluting is surrounded by a concave footslope, whereas on the slope gradient map, the flat top of the fluting is associated with low slope gradients of 0 to 2 percent and the hillslopes are presented by slope gradients of 5 to 9 percent. This fluting is incorporated on the surficial geology map within the landform unit *hummocky-rolling(1-10m)* and differentiated as a separate unit from the surrounding *undulating* landform as *hummocky* on the soil survey map.

Hummocky-rolling units describe a landform category not defined by the soil survey. The category *hummocky-rolling* consists of *rolling* landforms draped by hummocks. Individual hummocks can be especially well differentiated on all DTMs in the northwestern part of the study area by their rounded form, flat, convex tops and circular delineation of concave footslopes. *Hummocky-rolling* landforms are divided into medium and high relief units. The medium relief units are associated with some of the flutings in the central and northwestern part of the study area, and within the eastern margin of the thrust moraine separating the eastern *level* to *undulating* landforms from the *rolling* to *ridged* landforms in the central part of the study area. Most of these units have been labelled *hummocky(5-9%)* and *hummocky-ridged(5-9%)* on the soil survey and *hummocky-rolling(1-10m)* and *ridged-rolling(3-10m)* on the surficial geology map. *Hummocky-rolling* landforms of high relief are located north, within, and south of the Beaver River meander neck and are partly dissected by fluvial processes. These areas are defined as *hummocky(9-15% and >15%)* on the soil map, and *rolling(3-10m and >10m)* and *hummocky-rolling(3-10m)* on the surficial geology map.

Ridged landform units are differentiated from rolling landform units according to the Canadian System of Soil Classification (E.C.S.S., 1987a) by a "sharp crested" in comparison to a more "rounded" *rolling* landform (Table A1.1). A *ridged* landform unit labelled as *hummocky-ridged(9-15%)* on the soil survey map is delineated in the central part of the study area. This particular unit is not differentiated as a separate unit on the surficial geology map, while a triangular feature in the northeast of the study area is defined as *ridged* on the surficial geology map. The triangular form is caused by the arrangement of three landform features, two ridges and a hummock. The two ridges were formed behind the outcrop of bedrock which appears as a rounded hill.

Hummocky-ridged units are composed of ridged landforms draped by hummocks and dissected by fluvial processes especially in areas of high altitude in the south and central part of the study area. The parallel alignment of these incisions is clearly recognizable on the DTMs. These units have been labelled *hummocky-rolling(1-10m)* or *hummocky-ridged(>3m)* on the surficial geology map and *hummocky* composed of a variety of slope gradients on the soil survey map.

One of the most striking units visible on the DTM maps portrays a field of *hummocky* landforms located in the southwest of the study area. This unit consists of irregular knobs and kettles without any main drainage lines visible and is associated with *hummocky* landform units on both, the surficial geology map and soil survey map. Areas defined as *hummocky-inclined* on the soil survey map and described according to Brierley *et al.* (1990) as "sloping, unidirectional surface not broken by marked irregularities" cannot be differentiated as such on the DTM.

The last units considered are associated with the Beaver River drainage way and the most prominent creeks in the study area, such as St. Lina Creek (Figure 3.2 and 3.3). The steeply incised valley walls of the creeks and the Beaver River are especially well delineated on the DTMs by high relief, steep slopes, and high concavities and convexities. This unit is classified as *dissected* on the DTM landform map (transparency) and is labelled as *varied* on the surficial geology map. On the soil survey map, the creeks and the steep banks of the Beaver River are separated into two different categories. Creeks are labelled as *level(0-10%)* whereas the Beaver River valley walls are labelled as *dissected*. Neither *dissected* nor *varied* are described as a surface expression in the Canadian System of Soil Classification (E.C.S.S., 1987a) and the Terrain Classification System (Howes and Kenk, 1988) but are defined in Table A1.3 according to the County of St. Paul soil survey and the Sand River Surficial geology survey. The two categories are characterized by erosional and depositional processes such as gullying and mass movement. The location of *terraces* delineated on the surficial geology map can only be guessed on the hillshaded and curvature model maps because of their similarity in appearance to landslides. Both forms, terraces and landslides, are characterized by a step-like appearance represented as convex-straight-concave sequence on the curvature map. The floodplain of the Beaver River is separately specified as *level*, labelled as *flat* on the surficial geology and *level(0-10%)* on the soil survey map. The extent of the floodplain is well delineated on the slope gradient map represented by slope gradients of 0 to 2 percent.

4.4 Summary

The use of DTMs in landform mapping improves the traditional method of image interpretation by providing a more flexible and quantifiable data source than airphotos or topographic maps. The application of automated modelling and display techniques allows the fast adjustment of DEMs according to specific characteristics of the terrain and the specific objective of the mapping project by generating appropriate DTMs, and by selecting suitable enhancement techniques to portray landforms. As a consequence, maps of DTMs provide suitable graphical displays for the qualitative interpretation of landform categories as defined by soil and surficial geology surveys. Hillshaded models are particularly useful for the identification of surface expression which cannot be delineated as easily on maps of local relief, slope gradient and curvature models. Burrough (1986) argued that detail is lost on hillshaded model maps in comparison to airphotos due to smoothing of the digital data sets. Instead, the analysis showed, detail can be enhanced by increasing the contrast of the hillshaded model, which can be achieved by changing the solar azimuth, decreasing the solar elevation, and increasing clipping levels of the grey scaled map. The selection of the appropriate solar elevation and solar azimuth is important, in particular, when displaying hillshaded models containing unidirectional features such as flutings.

Using a classed grey scale instead of a continuous grey scale to display the DTMs of local relief, slope gradient and curvature is inefficient for detecting detail, such as the identification of poorly drained depressions. In contrast, the division of grey scale values into a series of steps contributes to the readability especially of drainage lines which are particularly well shown on downslope curvature maps. The display of downslope curvature models, however, has the drawback of being susceptible to the display of noise, such as the appearance of grid sampling lines even after the data sets have been smoothed. As a result of an increasing roughness found in higher order derivatives (Burrough, 1986), the use of second order derivatives of elevation, such as curvature models, have been recommended by Johnson (1988) and Evans (1980) as a method for checking compilation and surfacing errors in the production of DEMs.

The interpretation of landform categories from DTM maps is still regarded as a qualitative analysis based on the landscape approach rather than a quantitative analysis based on the parametric approach to landform mapping (Cooke and Doornkamp, 1990; Van Zuidam 1986). For this reason, the interpretation of landform categories from DTM maps has not yet provided a method for the generation of objective, reliable and reproducible landform maps. As apparent from the landform maps of the study area, the landform units of surface expression interpreted from the DTMs do not coincide in all instances with the landform units delineated on the soil and surficial geology maps. This inconsistency is caused by several facts. First, the definition of surface expression varies between the Canadian Soil Survey Classification, the Terrain Classification System, the County of St.Paul soil survey, and the Sand River geology survey. On the soil and surficial geology landform maps of the study area, different categories are assigned for surface expression and units do not coincide in their areal extent between the two surveys. Second, qualitative landform mapping is based on image interpretation which is subjective to the operator's judgement, expertise and knowledge of the area and to the quality of the data sources. To provide a more reliable landform map, not only the data sources must be made quantifiable but the process of landform mapping has to be automated. A first step towards achieving this goal is the determination of homogeneous landform units representing individual morphometric variables based on numerical terrain analysis techniques. This task will be the focus of the next chapter.

5. Mapping of Morphometric Modifiers Using Neighbourhood Processing Functions

The objective addressed in this chapter focuses on the development and application of an automated technique for mapping homogeneous units of morphometric modifiers, as represented on the County of St. Paul soil map (Brierley *et al.*, 1990) and the Sand River surficial geology map (Andriashek and Fenton, 1989). On these maps, morphometric modifiers of slope gradient and local relief are specified for entire landform units. According to Brierley *et al.* (1990), slope gradient refers to the dominant slope class within a landform unit whereas local relief is defined by Andriashek and Fenton (1989) as the average difference in elevation between a hill or ridge and an adjacent depression within a particular landform unit. Slope gradient and local relief, mapped in Chapter 4 as classed grey scale digital terrain model (DTM) maps (Figure 4.3 and Figure 4.4), do not conform with the specification of morphometric modifiers as mapped on the County of St. Paul soil map and the Sand River surficial geology map. Instead of presenting homogeneous morphometric units, the DTM maps portray heterogeneous grid cell patterns of classed slope gradient values. To map homogeneous morphometric units, the morphometric modifiers must be determined for units larger than the single grid cells used previously in automated mapping techniques. In the County of St.Paul soil survey and the Sand River surficial geology survey, those homogeneous units are represented by recurrent landform patterns which can be delineated using manual mapping techniques. However, the delineation of homogeneous landform units using automated mapping techniques is complex. As a result, the landform units are replaced in this research by neighbourhoods which can be incorporated into an automated mapping process using neighbourhood processing functions.

Two neighbourhood processing functions, a filtering algorithm and a function for determining local relief, are introduced in this research for mapping morphometric modifiers. Filtering techniques are used to simplify the information contained in the DTM. Such a simplification can be achieved by reducing the small scale variation or texture of the DTM through statistical generalization (Brassel and Weibel, 1988). As a result, the size of the neighbourhood, over which the DTM is filtered, must be large enough to filter out the small scale variation determined by texture measurements. Filtering techniques are used in this chapter to smooth the slope gradient and curvature DTMs.

The determination of local relief is not based on a function designed to reduce the variation or texture of a DTM but is based on a measure designed to calculate the vertical variation of elevation. As for the filtering process, the selection of an appropriate neighbourhood size is essential for determining local relief. Local relief derived from a 3x3 neighbourhood described in Chapter 4 (Figure 4.3) does not cover the full elevation range between a hill and depression (Andriashek and Fenton, 1987) but becomes a measure of slope gradient (Evans, 1972). As a consequence, the size of the neighbourhood, from which local relief is derived, must measure at least the distance between major ridges and channels defined as grain (Pike et al., 1989).

The first step of this research involves the determination of neighbourhood sizes according to texture and grain analysis. As a second step, neighbourhood processing functions are used to derive, numerically, accurate morphometric modifiers of local relief, slope gradient and downslope curvature from such units. Finally, the resulting DTM maps are interpreted and visually compared with the Sand River surficial geology map and the County of St. Paul soil map to assess the correspondence between morphometric units mapped according to automated techniques and morphometric units mapped according to manual techniques.

5.1 Determination of Neighbourhood Sizes Based on Texture and Grain Analysis

To describe the method for the determination of the optimal neighbourhood size used in neighbourhood processing, a parallel is drawn to image interpretation techniques used to map landform units manually. In image interpretation the continuum of the land surface shown on the image is divided by the human eye/brain system into a number of viewing fields of greater homogeneity than the continuum as a whole (Dobson, 1973). The size of the viewing field is dependent on the complexity and spatial variability of the land surface which is categorized according to pattern and texture as described in the previous chapter. In computer mapping, the viewing fields become neighbourhoods and the determination of the neighbourhood sizes becomes a function of pattern variation.

The variation of landform patterns in the horizontal dimension has been defined by grain and texture. Grain refers to the coarse scale or long wave landform variation whereas texture is defined by the fine scale or short wave landform variation (Evans, 1972; Mark, 1975). The long wave landform variation is associated with the spacing of major ridges and channels (Wood and Snell, 1960), which determines the size of the area, from which local relief is derived. For this reason, grain analysis has been used to select the appropriate neighbourhood size for the determination of local relief (Pike *et al.*, 1989). Additionally, Pike (1988) proposed the application of grain analysis for selecting optimal neighbourhood sizes over which any terrain parameter can be measured. In contrast, the objective of filtering DTMs is the reduction of small scale variation represented by texture not the reduction of large scale variation as determined by grain. For this reason, the use of grain analysis is not the appropriate method for determining the neighbourhood size used in a filtering process. As Weibel and DeLotto (1988, p.623)) pointed out "the use of grain for the determination of window size is not always recommendable, depending on the objective of the classification. Rather than setting the window to the grain, it has to be tailored to the wavelength of the fundamental texture elements of the topographic sample". Consequently, two different methods are used in this thesis to analyse the landform variation: first, texture analysis is used to determine the neighbourhood size for filtering the DTMs; and, second grain analysis is used to determine the neighbourhood size for deriving local relief.

5.1.1 Grain Analysis

The grain of landform variation has been determined by Wood and Snell (1960) using a method first described by Gutersohn (1932). According to the method, the highest and lowest elevation points are plotted against a radial distance from randomly selected points represented in a relief/area curve. If the full range of local relief is reached, the relief/area curve increases at a smaller rate for an increase of radial distance. This break point of the curve is called the *knick* (Gutersohn, 1932) and indicates the longest wavelength or grain of a land surface. Pike *et al.* (1989) automated this method by plotting the elevation range and standard deviation for increasing neighbourhood sizes of a DEM. The measurement of grain as described by Pike *et al.* (1989) corresponds with the concept of autocovariance. The concept of autocovariance has been used by Oliver and Webster (1986), Kundert (1988, cited in Weibel (1989)), and Weibel and DeLotto (1988) to determine grain from semivariograms, whereas Pike and Rozema (1975) derived grain from periodicities of a power spectrum.

Problems are however associated with the use of the semivariogram and spectral analysis. Tests by Weibel (1989) revealed that different methods for semivariogram estimation and different runs with the same method yielded different results. Spectral analysis proved to be affected by edge effects, aliasing (distortion of the spectrum by wavelengths shorter than twice the sampling interval) and a directional bias (Weibel and DeLotto, 1988). As a consequence, the less elaborate method of a relief/area curve described by Pike *et al.* (1989) was implemented in this research. The mean elevation range and standard deviation for increasing neighbourhood sizes were plotted for the total study area (Figure 5.1) and separately for the individual geology landform categories (Figure 5.2.1 to 5.2.3). Only landform categories, which cover more than 1 percent of the total study area, were considered in the relief/area curve. Landform categories of less than 1 percent coverage were omitted because edge effects would have become too large and would have influenced the accuracy of the analysis.

5.1.2 Texture Analysis

Texture measures as used in landform classification have been developed using first and second order statistics (Franklin and Peddle, 1987), power spectra (Rayner, 1971; Pike and Rozema, 1975), semivariograms (Oliver and Webster, 1986; Weibel and DeLotto, 1988; Weibel, 1989) and fractal dimensions (Mark and Aronson, 1984; Goodchild and Mark, 1987). A study by Weszka *et al.* (1976) revealed that first order statistics performed comparably if not better than second order statistics or Fourier power spectra in texture analysis. Problems related to the use of cooccurrence matrices, power spectra, semivariograms and fractal dimensions in landform texture analysis have been discussed by Weibel and DeLotto (1988) and Weibel (1989). As a result, the texture analysis used in this research is based on first order statistics which are also easier to implement than the methods referenced above.

First order statistics, such as the coefficient of variance, relative variance and intraclass correlation, have been used to evaluate the accuracy and efficiency of soil and terrain classifications by testing the homogeneity of map units (Webster and Beckett, 1970; Bie and Beckett, 1971; Beckett and Webster, 1971; Beckett and Burrough, 1971; Van Zuidam, 1986). The coefficient of variance is an absolute measure of homogeneity and compares the standard deviation to mean ratio of a map unit with a predetermined threshold value of homogeneity. In contrast, the relative variance and intraclass correlation are relative measures of homogeneity. The relative variance compares the within unit variance with the total variance, whereas the intraclass correlation compares the between unit variance with the total variance. Both measures are based on the assumption that the variance within the map units is smaller than the variance between the units for homogeneous map units. Recently, a third measure of separability has been introduced by Gong and Howarth (1992) which compares the between and within unit variance. However, the method has not been effective in predicting the optimal grid neighbourhood size.

In this thesis, relative variance was used to determine the optimal neighbourhood size according to texture analysis. With respect to the determination of grain, the relative variance is calculated for increasing neighbourhood sizes of up to 19x19 grid points and plotted against a 0.5 relative variance (relative variance values range from 0 for highest homogeneity to 1 for lowest homogeneity within the landform units, whereas 0.5 relative variance forms the break point between an equal within and between variance). If the relative variance exceeds a value of 0.5, the within variance is greater than the between variance and the homogeneity within the neighbourhoods is less than between the neighbourhoods. Consequently, the neighbourhood size is too large to contain a homogeneous texture pattern and the next smaller neighbourhood size is selected as the optimal size.

In the existing literature reviews, relative variance has not been used for determining neighbourhood sizes for the use in landform mapping. As a result, the break point of 0.5 relative variance as a threshold for determining sufficient homogeneity within the map units has to be reviewed because standards for thresholds have not been set before. Furthermore, to understand the behaviour of relative variance in landform mapping and the possibility of using the parameter as a measure for determining neighbourhood sizes, relative variance has to be assessed in as much detail as possible. For this reason, relative variances of elevation, slope gradient and curvature were calculated for the total study area. And additionally, the relative variances of slope gradient were plotted for the different soil landform categories to estimate texture variation between different landform types.

5.2 Results of Grain and Texture Analysis and Their Implication for the Selection of Neighbourhood Sizes

5.2.1 Selection of the Optimal Neighbourhood Size for Determining Local Relief

Local relief was plotted against increasing neighbourhood sizes for the entire study area according to the mean range and mean standard deviation of elevation (Figure 5.1). The relief/area curve based on mean range measurements represents higher local relief values for the same neighbourhood sizes than the values of the relief/area curve based on standard deviation measurements. This difference is the result of the range representing the extreme values of local relief, whereas the standard deviation represents more stabilized local relief values (Evans, 1972). Although the rate of increase in the values of the two curves gradually diminishes, no abrupt break point or *knick* representing the grain within the study area is apparent. Even the curves illustrating local relief for the individual geology landform units (Figures 5.2.1 to 5.2.3) have no *knick*. The *knick* might be absent because the largest neighbourhood size of 19x19 equalling a diameter of 475 meters was selected at a size too small to reach the *knick*. Grain analysis by Pike *et al.* (1989) implemented for 1:24,000 and 1:250,000 DEMs portrayed *knicke* at greater than 1 km distance. However, the grain was derived by Pike *et al.* (1989) for landform samples of medium to high relief whereas the landform samples considered here are at least one order of magnitude lower in relief.

To determine a neighbourhood size for calculating local relief in this research, the curves are plotted against 3 and 10 meter relief values used as class limits on the Sand River surficial geology map (Fenton and Andriashek, 1983). The range of neighbourhood sizes, for which the local relief values associated with the landform units can be accurately determined, were derived from these curves (Figure 5.2.1 to 5.2.3) and are shown in Table 5.1. The ranges were The most frequently occurring neighbourhood sizes are 5x5 and 7x7 for local relief derived from the range and 7x7 and 9x9 for local relief derived from the standard deviation. A neighbourhood size of 7x7 grid points was selected to derive local relief class limits comparable to the ones used on the surficial geology map. This neighbourhood size was selected based on visual inspection of local relief range

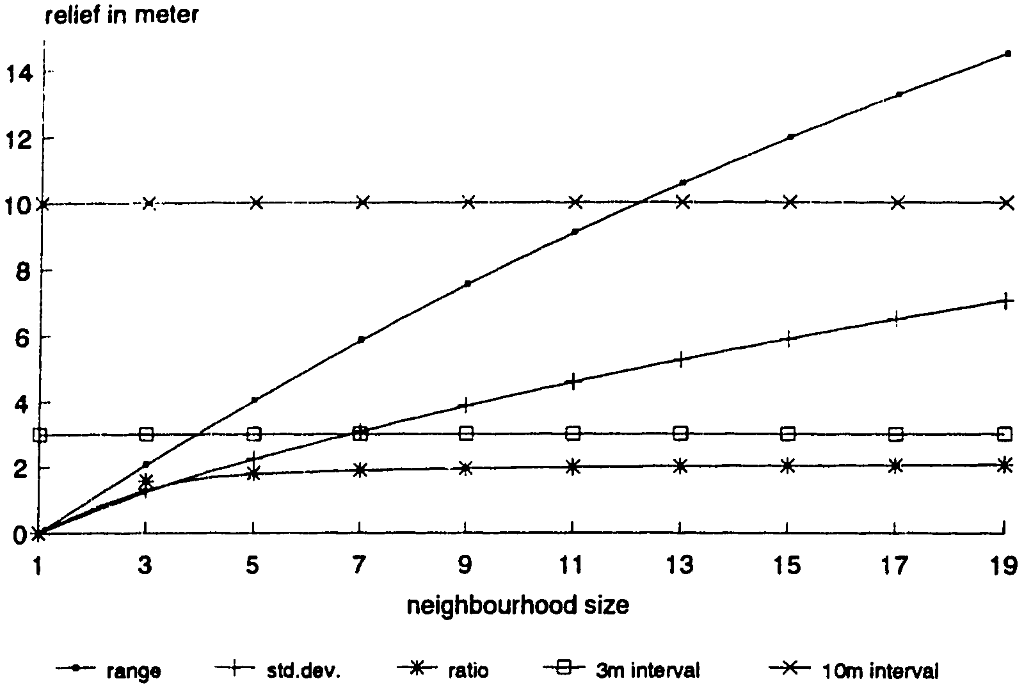
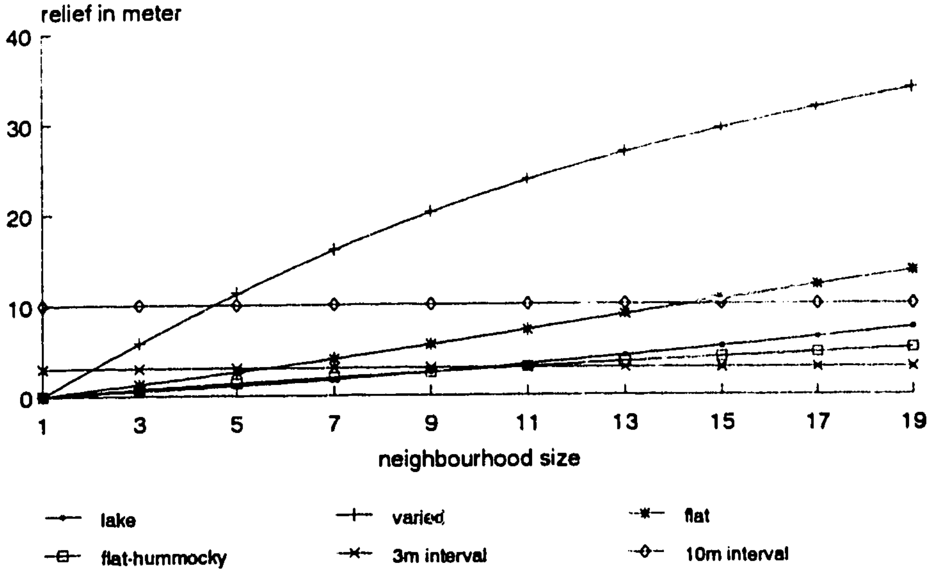
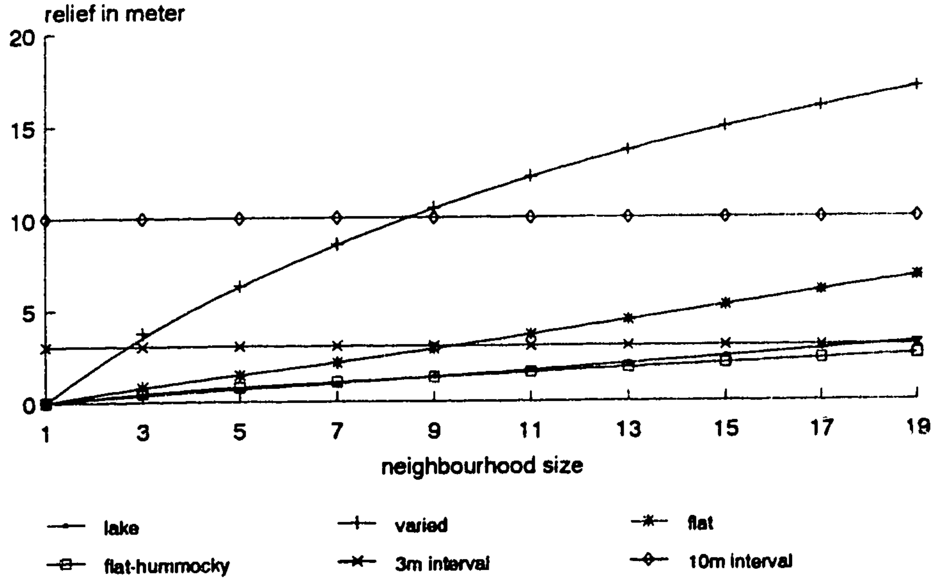


Figure 5.1. Mean local relief of total study area for increasing neighbourhood sizes



Range



Standard Deviation

Figure 5.2.1. Mean local relief of geology landform categories 1 for increasing neighbourhood sizes

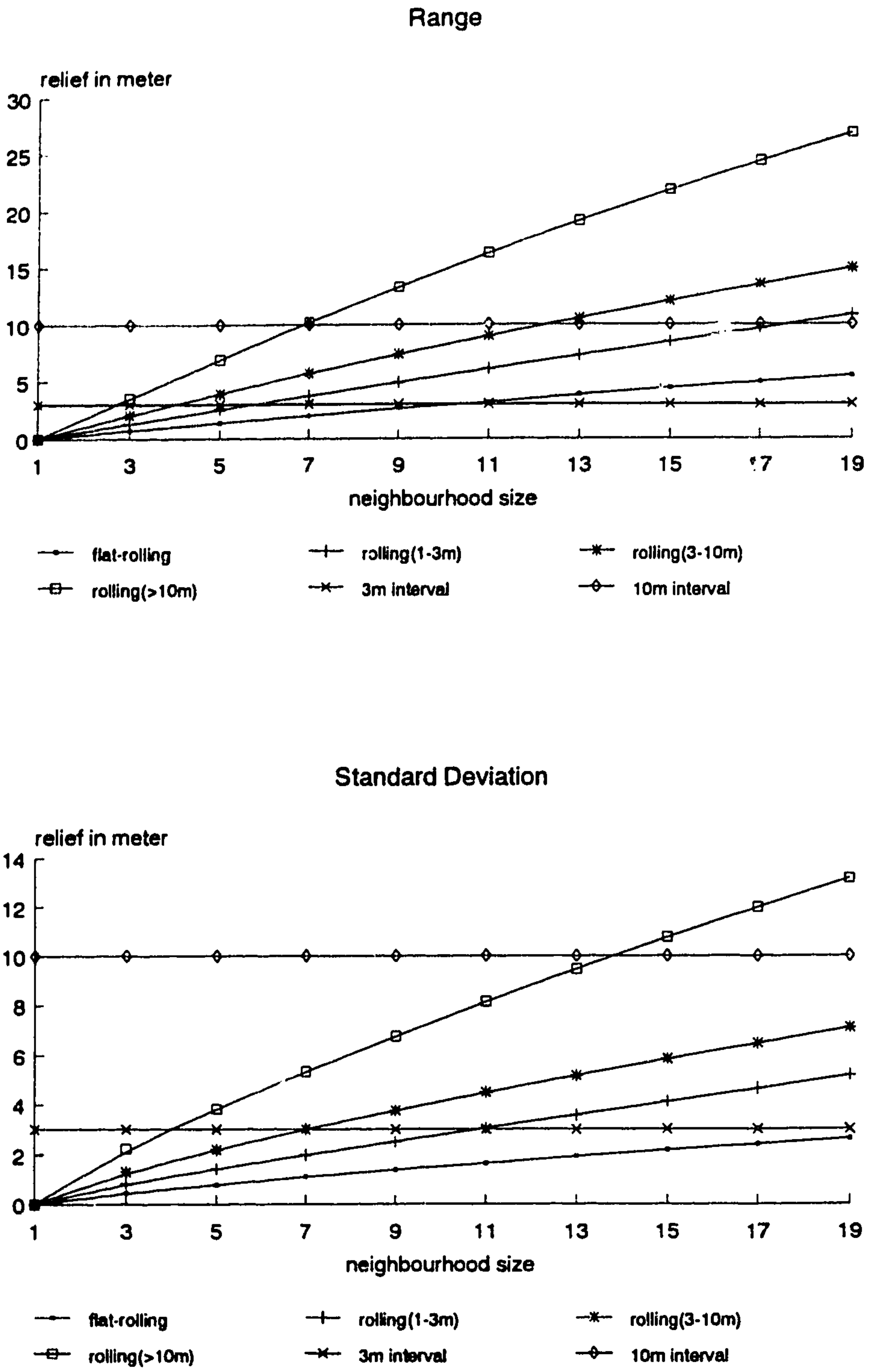
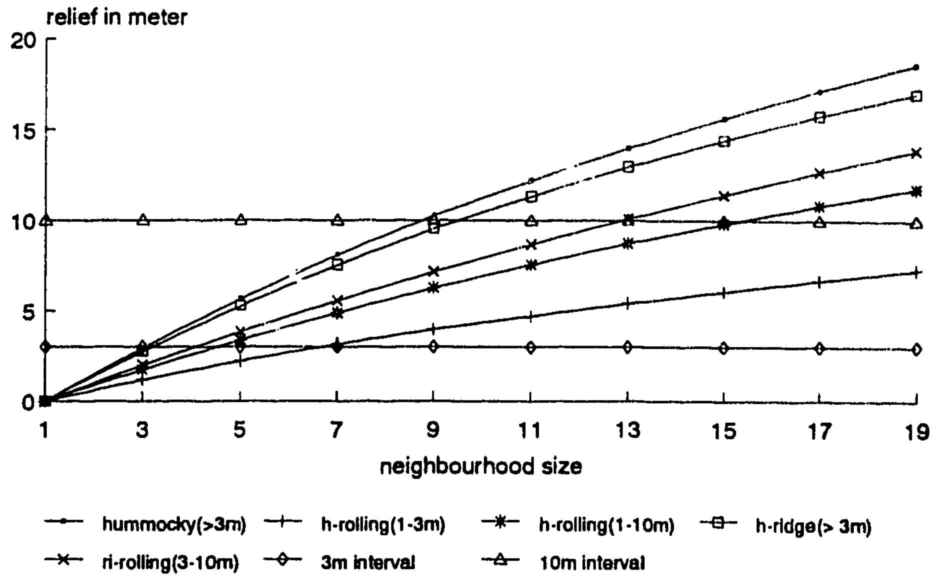


Figure 5.2.2. Mean local relief of geology landform categories 2 for increasing neighbourhood sizes

Range



Standard Deviation

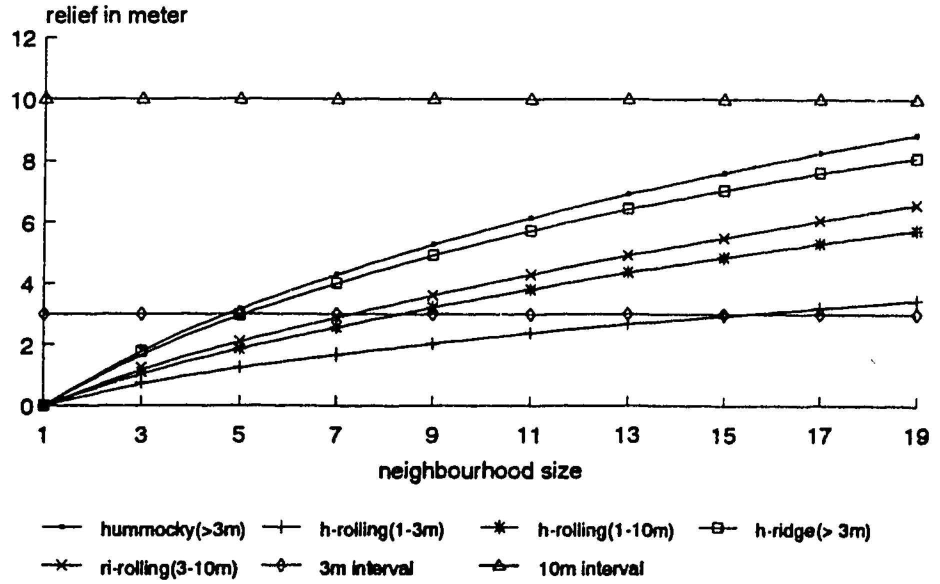


Figure 5.2.3. Mean local relief of geology landform categories 3 for increasing neighbourhood sizes

Table 5.1. Range of Neighbourhood Sizes for the Assessment of Local Relief Distributions According to Geology Landform Category Modifiers

Landform category	Neighbourhood-size <u>based on range</u>		Neighbourhood size <u>based on std.dev.</u>	
	lower	upper	lower	upper
Lake		5x5		7x7
Varied	2x2		3x3	
Flat		5x5		9x9
Flat-Rolling		10x10		>19x19
Rolling(1-3m)	2x2	6x6	4x4	11x11
Rolling(3-10m)	4x4	12x12	7x7	>19x19
Rolling(>10m)	7x7		14x14	
Flat-Hummocky		11x11		>19x19
Hummocky(>3m)	3x3		5x5	
Hum-Rolling(1-3m)	3x3	7x7	4x4	15x15
Hum-Rolling(1-10m)	2x2	15x15	3x3	>19x19
Hum-Ridged(>3m)	3x3		5x5	
Ridge-Rolling(>10m)	4x4	15x15	7x7	>19x19

maps generated for different convolved neighbourhood sizes (not shown in this thesis) and further statistical analysis presented in chapter 6.

The selected neighbourhood size is far smaller than those referenced in the literature. Pike (1988) based his classification of landform types on a neighbourhood size of 21x21 for a grid resolution of 30 meters. Weibel and Heller (1991) used a neighbourhood size of 13x13 for a grid resolution of 25 meters. However, these neighbourhood sizes were derived for landforms of higher relief than those present in the study area. Automated analysis for the purpose of determining the grain of low relief terrain has not been reported in the literature. Furthermore, the selection of small neighbourhood sizes for this research can also be related to an underestimation of the local relief class limits defined by Andriashek and Fenton (1989).

5.2.2 Selection of the Optimal Neighbourhood Sizes for Filtering Slope Gradient and Curvature DTMs

The selection of the neighbourhood size for map generalization using a filter function involves a tradeoff between accuracy and simplicity. If too large a neighbourhood size is selected, too much detail may be lost, whereas if too small a neighbourhood size is determined the map may not be sufficiently generalized. Sufficient accuracy is maintained as long as the neighbourhood size stays below the size derived for the threshold value of 0.5 relative variance. Prior to mapping, a level of generalization is often set by the cartographer in the form of a minimum size for map delineations to achieve an optimal visual effectiveness of the map (Brassel and Weibel, 1988). Such minimum delineation sizes have been set by the E.C.S.S. (1987b) for mapping units in Canadian soil surveys allowing for a smallest "optimal" landform unit delineation of 0.5 cm^2 and a smallest "possible" delineation of 0.25 cm^2. Since the soil survey map of the County of St. Paul is mapped at a scale of 1:50,000, a landform unit of 0.5 cm^2 covers an area of 354x354 meters. Given a grid resolution of 25 meters, this area translates into a neighbourhood size of 14x14 grid cells. A delineation of 0.25 cm^2 would cover an area of 250x250 meters equivalent to a neighbourhood size of 10x10 grid cells. These neighbourhood sizes represent the recommended level of generalization and are compared with those derived from relative variance analysis which represent the determined level of accuracy.

To assess the texture of different morphometric modifiers, the relative variance curves of elevation, slope gradient and downslope curvature (Figure 5.3) are analysed for the total study area. The relative variance for elevation increases notably less than for slope gradient and is lower than the threshold of 0.5 relative variance for a neighbourhood size of 19x19. The course of the curve confirms the results of the grain analysis. The *knick* was never reached for a neighbourhood size of 19x19 because the variation of elevation in the study area is so minimal. As a result, the DEM does not need to be filtered at all because the neighbourhood size lies beyond the maximum neighbourhood size selected for this research.

The curve representing relative variance of slope gradient approaches the threshold of 0.5 relative variance at a neighbourhood size of 19x19 whereas the curve of downslope curvature crosses the threshold of 0.5 relative variance at a 4x4 neighbourhood size. The increase in relative variance from elevation to downslope curvature reflects the statement by Burrough (1986) that the roughness of DTM data increases with the order of the derivative described in chapter 4. Consequently, different neighbourhood sizes, which may not conform with the level of generalization set prior to mapping, have to be selected for generalizing various DTMs. For example, a smaller neighbourhood than that recommended by the E.C.S.S. has to be used to filter the downslope curvature DTM. A neighbourhood size of 5x5, slightly larger than the threshold neighbourhood size of 4x4, was eventually selected to filter the curvature DTM. This neighbourhood size was determined after visual inspection of curvature maps filtered for various convolved neighbourhood sizes (the different filtered curvature maps are not shown here) by giving simplicity preference over accuracy. The curvature map would not have been generalized sufficiently if a neighbourhood size of 3x3 had been used.

Before selecting the neighbourhood size to filter the slope gradient map, the relative variances for the individual soil landform units are examined (Figure 5.4). The result of the analysis is indicated in Table 5.2 which represents the total variances of the individual soil landform units and the neighbourhood sizes at a relative variance of 0.5. The curves of relative variance reveal that the variances vary according to changes in terrain roughness. Generally, landform types of smooth texture, such as *level(0-2%)* and *undulating* are associated with a relatively low relative variance and, consequently, the filtering process can be applied over larger neighbourhoods. In contrast, landform categories of high variation such as *dissected* associated with the river banks, *level(0-10%)* representing creeks, and *hummocky*

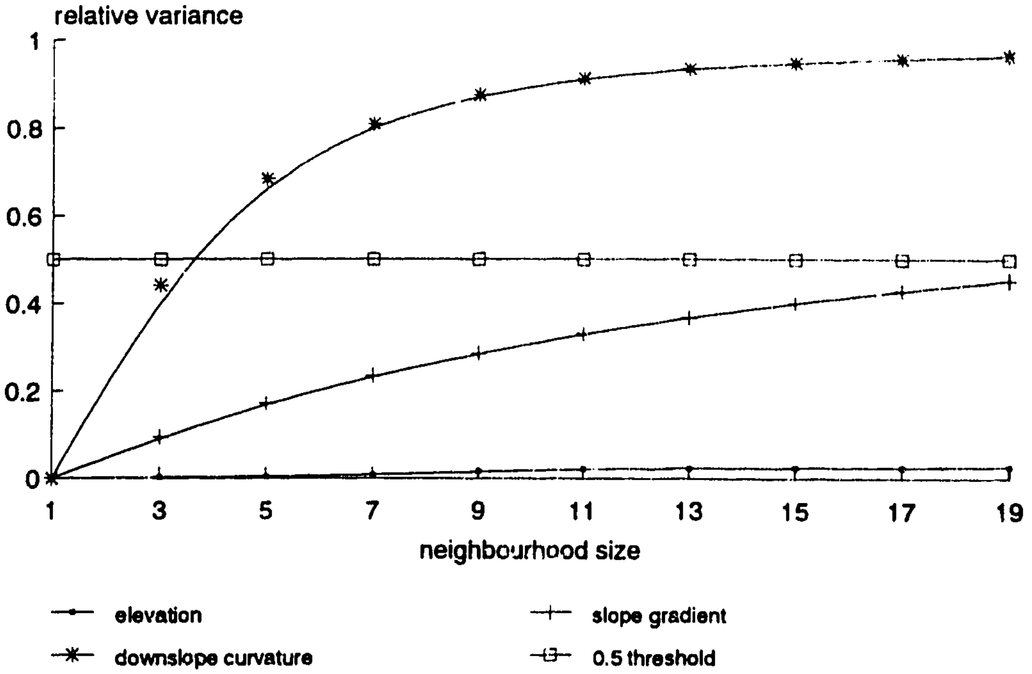
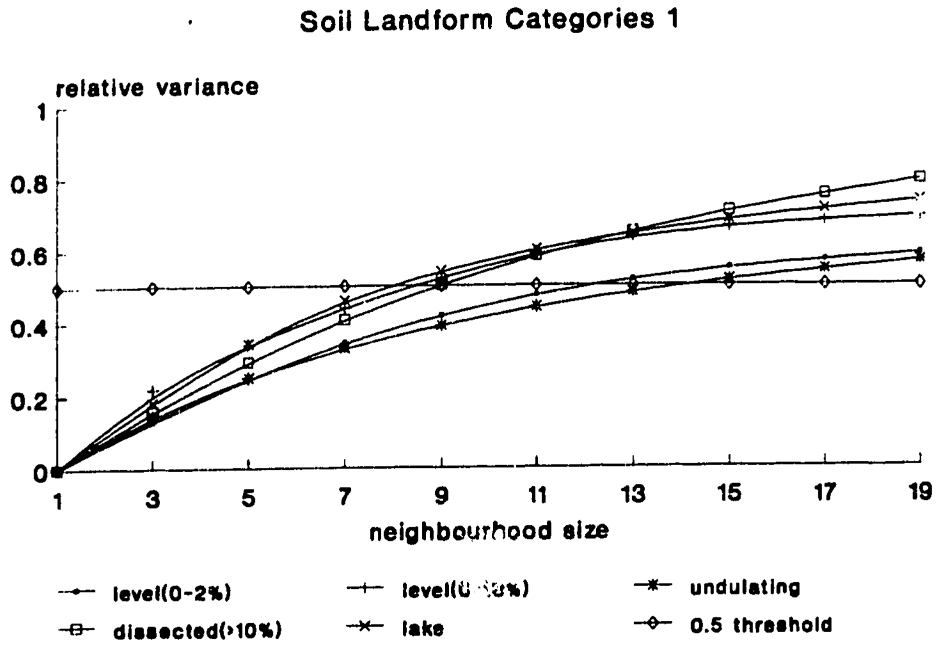


Figure 5.3. Relative variance of elevation, slope gradient and downslope curvature distributions for study area according to increasing neighbourhood sizes



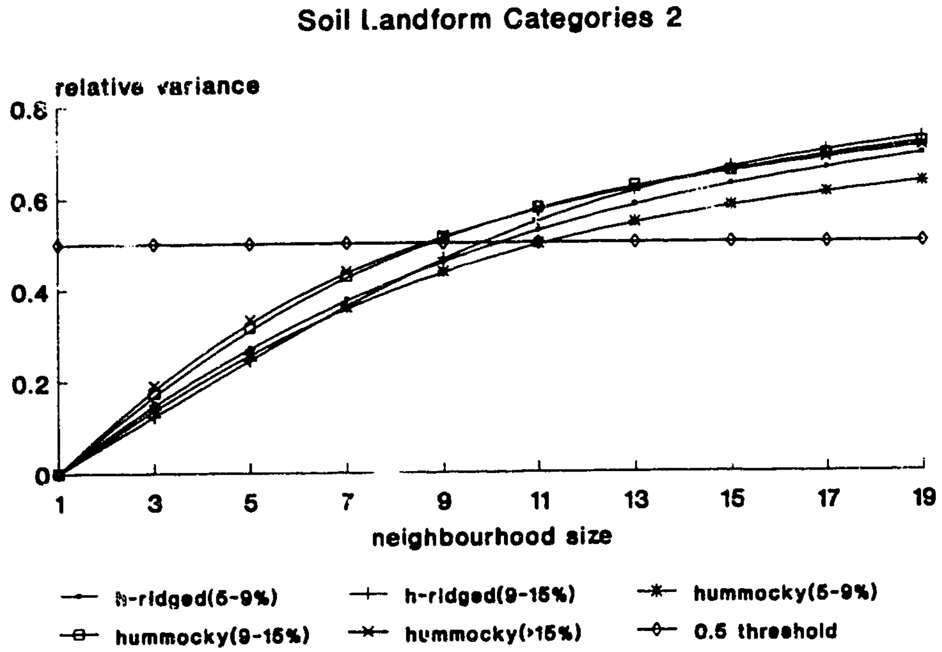


Figure 5.4. Relative variance of slope gradient distribution for soil landform categories according to increasing neighbourhood sizes

Table 5.2. Total Variance and Optimal Neighbourhood Size of Slope Gradient Distribution for Soil Survey Landform Categories

Landform category	Total variance	Neighbourhood size at 0.5 relative variance
Total study area	4.361	>19x19
Lake	0.578	8x8
Level(0-2%)	0.991	12x12
Level(0-10%)	4.816	8x8
Undulating(2-5%)	1.020	14x14
Dissected(>10%)	7.570	9x9
Hum-Ridged(5-9%)	1.090	10x10
Hum-Ridged(9-15%)	1.567	10x10
Hummocky(5-9%)	1.571	11x11
Hummocky(9-15%)	3.024	9x9
Hummocky(15-30%)	4.716	9x9

units of slope gradients greater than 9 percent have the highest relative variance and have to be filtered over smaller neighbourhood sizes of 8x8 and 9x9.

Furthermore, the unit *lake* shows a large increase in relative variance although the unit itself is regarded as the smoothest landform in the study area. This abnormality is related to the way relative variance is calculated as the ratio of the within variance to the total variance. The unit *lake* represents the lowest total variance in the study area (Table 5.2). Any slight variation in the within variance increases the relative variance overproportionally which is caused by the low total variance. The reverse may be true for very rough landforms such as the dissected valley walls. The unit *dissected* represents the highest total variance within the study area, however, the reported relative variance is not higher than the one for landform categories *hummocky(9-15%)* and *hummocky(>15%)*.

The unexpected relative variance values may not only be related to an extreme high or low total variance but also to an edge effect caused by the neighbourhood analysis. For increasing neighbourhood sizes more and more slope values are included in the neighbourhood which may not belong to the landform unit. In the case of the *dissected* units, lower slope values outside of the landform unit decrease the within variance of the neighbourhoods in comparison to the total variance which results in a lower than expected relative variance. Consequently, the use of relative variance to determine neighbourhood sizes has to be cautioned for areas of small areal extent, narrow shape or extreme total variance.

The optimal neighbourhood size of 19x19 grid cells derived from the relative variance curve for the total study area is far larger than the sizes derived for the individual categories. Consequently, the neighbourhood size derived for the total study area should not be binding for the determination of the optimal neighbourhood size. Rather, smaller training units representing different landform variations should be selected and their relative variance tested individually. However, as presented for the different landform categories of the soil survey map, the neighbourhood sizes vary between the different landform types and can only act as a margin within which the optimal neighbourhood size is selected. For the landform categories of the County of St.Paul soil survey map, the neighbourhood sizes fluctuate between 8x8 and 14x14, averaging to a neighbourhood size of 10x10. The neighbourhood sizes recommended by the E.C.S.S. are comparable to the ones derived from the relative variance measurements. Any neighbourhood size between 10x10 and 14x14 can be selected according to the E.C.S.S.. However, an odd neighbourhood size is required to determine the filtered value for the centre grid point of a neighbourhood. Eventually, a lower neighbourhood size of 11x11 was selected to also represent *hummocky* landforms in the study area as accurately as possible. The neighbourhood size selected is comparable to that used by Weibel (1989) of 13x13 for a grid resolution of 25 meter.

5.3 Implementation of Neighbourhood Processing Functions

In neighbourhood processing, each grid cell value is replaced with a value calculated for a convolved neighbourhood. The following two neighbourhood processing functions were used to generate DTMs: first, the range was used to generate the local relief model; and, second, a modal filter was used to generate smoothed slope gradient and downslope curvature models. When using neighbourhood processing functions, the following drawback has to be considered. Dependent on the size of the neighbourhood, a band of rows and columns of grid cells consisting of half the neighbourhood size is lost around the margins of the data set. This edge effect results from the use of large convolution neighbourhoods. At the margins of the data sets, grid cells are not surrounded by the full neighbourhood size. As a result, these grid cells were not included in the neighbourhood process.

5.3.1 Function for Determining Local Relief

According to Evans (1972), the standard deviation of elevation provides a more reliable measure of local relief than the range which is based on the extreme values of the elevation variation. Using two standard deviation units, one at each side of the center of the distribution, the derived local relief values statistically represent only 68.4 percent of the elevation distribution from a neighbourhood. To consider 95 percent of the distribution, the standard deviation has to be multiplied by 1.96. Dividing the range by the standard deviation, the resulting ratio reaches a value of 2 for neighbourhood sizes of equal to and greater than 7x7, as illustrated in Figure 5.1. Given this result, the assumption was made for this research, that the range represents 95 percent of the elevation distribution. Consequently, the range, which is simpler and faster to calculate than the standard deviation, was used to derive local relief. After the local relief model had been generated, the DTM was classed according to the class limits used in the Sand River surficial geology survey (Andriashek [illegible], 1989; Table A1.4).

5.3.2 Modal Filtering Function

One of the objectives of the research described in this chapter is the application of a filtering technique that smooths the heterogeneous grid cell pattern of classed digital terrain models to form homogeneous units of dominant slope gradient and curvature class values. Several filtering techniques exist for this purpose, such as the average filter or the majority filter. Averaging is an appropriate filtering technique if ratio scale data are used, as is the case for the raw unclassed digital terrain models. But according to the County of St.Paul soil survey, the landform classification is based on classed slope gradient values. A majority filter is commonly used to smooth classed data sets by replacing the center grid cells of a neighbourhood with the dominant class value found within the neighbourhood (Schowengerdt, 1983). In this research, however, a more sophisticated filtering technique than the majority filtering technique was applied using both the ratio scale unclassed data set and the classed data set. The filtering technique is based on the calculation of the mode, as described by Bahrenberg and Giese (1975):

$$\text{Mode} = LCL + [(N_m - N_{m-1})/(2N_m - N_{m-1} - N_{m+1})] * RG$$

LCL = lower class limit of the majority class

N_m = number of values in majority class

N_{m-1} and N_{m+1} = number of values in neighbouring classes

RG = range of majority class limits

The calculation of the mode initially generated an unclassed ratio scale data set. The generation of a ratio scale data set has the advantage over the generation of a classed data set that the ratio scale data can be used in parametric statistical analysis and is not limited to the application of nonparametric analysis only. Furthermore, the use of modal filtering improves the accuracy of the filtered data because differences between the individual values within the class limits are maintained. This detail is lost when the filtering process generates a classed data set as is the case when majority filtering techniques are used. In a separate processing step, the modal filtered data sets were classed according to the class limits used by Brierley *et al.* (1990) for slope gradient (Table A1.4) and for downslope curvature according to Young's (1972) curvature classification scheme (Table A1.5).

5.4 Interpretation of Morphometric Maps

5.4.1 Local Relief Map

The classed local relief units on the DTM map derived for a convolved 7x7 neighbourhood (Figure 5.5) was visually compared with the landform units and associated local relief values portrayed on the Sand River surficial geology map (Figure 3.4). Overall, the polygons on the local relief model map are comparable to the same local relief categories represented on the Sand River surficial geology map. The *flat-rolling* to *flat-hummocky* units in the east of the Sand River surficial geology map, representing local relief values of 0 to 3 meters, can be easily differentiated on the local relief model map from the moderately *rolling* areas in the center of the study area, representing local relief values of 1 to 10 meters. In the west, south of the Beaver River, poorly drained depressions, specified as *flat* landform categories on the Sand River geology map, are just visible as units of low relief on the local relief model map. As presented on the Sand River geology map, units of *hummocky* landforms in the southwest tend to have also high local relief values of greater than 3 meters on the local relief model map. The highest relief in the study area are related to *varied* landforms representing the banks of the creeks and rivers which are also shown as areas of highest class values on the local relief model map. No relief modifier was associated with these landform units on the surficial geology map.

Flat areas representing the lakes and floodplains along the Beaver River are largely reduced in size on the local relief model map. The increase in elevation along the banks influences the local relief value up to half the distance of the neighbourhood size which is again a result of an edge effect caused by the use of neighbourhood processing functions. In some instances, for example along the lake shores, the square shape of the neighbourhood is visible and does not produce the preferred smooth polygon delineations.

5.4.2 Filtered Slope Gradient Map

The filtered slope gradient map obtained for convolved 11x11 neighbourhoods (Figure 5.6) was visually compared with the original classed slope gradient map. A simplified more readable map was produced as a result to

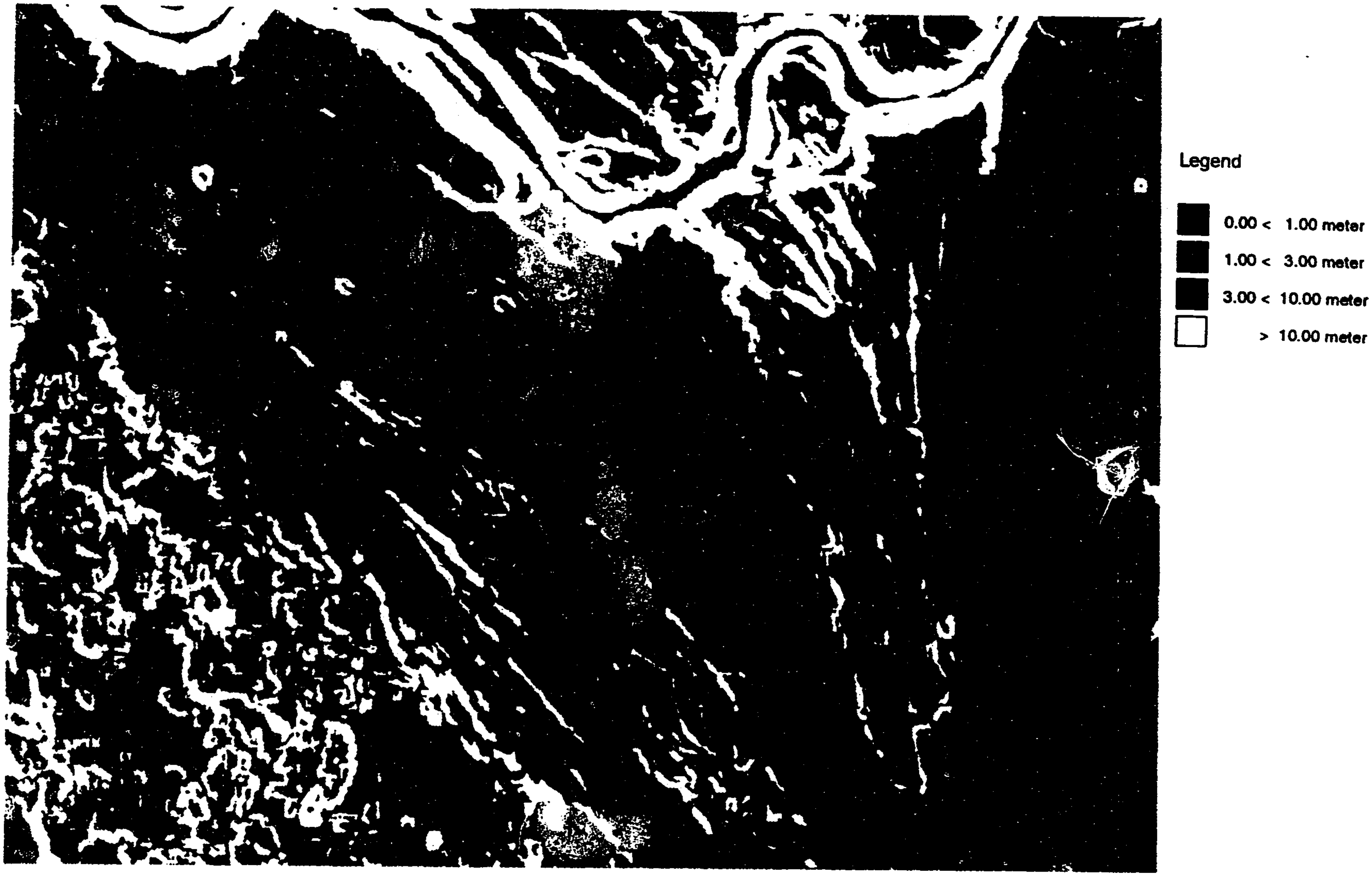


Figure 5.5. Local relief model, range derived for a convolved 7x7 neighbourhood

smoothing. Slope gradient units of large areal extent were created which can be associated easily with the classed slope gradient units on the County of St. Paul soil map (Figure 3.5).

The loss of detail caused by the neighbourhood process was not as extensive on the filtered slope gradient map as on the local relief map; the location of water courses of creeks (e.g. St.Lina creek in the center and south east), the Beaver River floodplain, the steep banks of the former glaciogenic spillway, the lakes to the southwest, and single hummocks or hills in the north west can easily be recognized on the filtered slope gradient map. Fine details, however, such as differences between creek valley bottoms and valley walls, differences between steeper slopes and flatter hill tops of hummocks and ridges, are lost on the filtered slope gradient map in comparison to the original slope gradient map. This detail, however, is not of importance for delineating homogeneous slope gradient units of large areal extent.

To evaluate whether or not the generation of homogeneous units is appropriate for landform mapping as determined by the County of St. Paul soil survey, the slope gradient class values portrayed on the filtered slope gradient model map were compared with the landform categories of the County of St. Paul soil survey map. Generally, the class values of the filtered slope gradient model map are lower than the values shown on the County of St.Paul soil survey map. These lower class values were also represented on the original slope gradient model map and are consequently not a result of the filtering process. Johnson (1988) and Niemann (1988) also concluded that slope gradient class values were lower on DTMs than on physical land classification maps of Alberta.

The difference in the slope gradient class values between the slope gradient model map and the County of St. Paul soil map amounts, in most instances, to one class interval. As a result, the slope gradient class differences are generally still distinguishable between the different landform units. For example, slope gradient model classes representing 2 to 5 percent slope correspond to soil survey classes representing 5 to 9 percent slope, and slope gradient model classes representing 5 to 9 percent slope correspond to soil survey classes consisting of 9 to 15 percent slope. In contrast, *level* units of 0 to 2 percent slope gradient cannot be differentiated from *undulating* units of 2 to 5 percent slope gradient on the slope gradient model map because both units are represented by the same class values of 0 to 2 percent slope on the slope gradient model map.

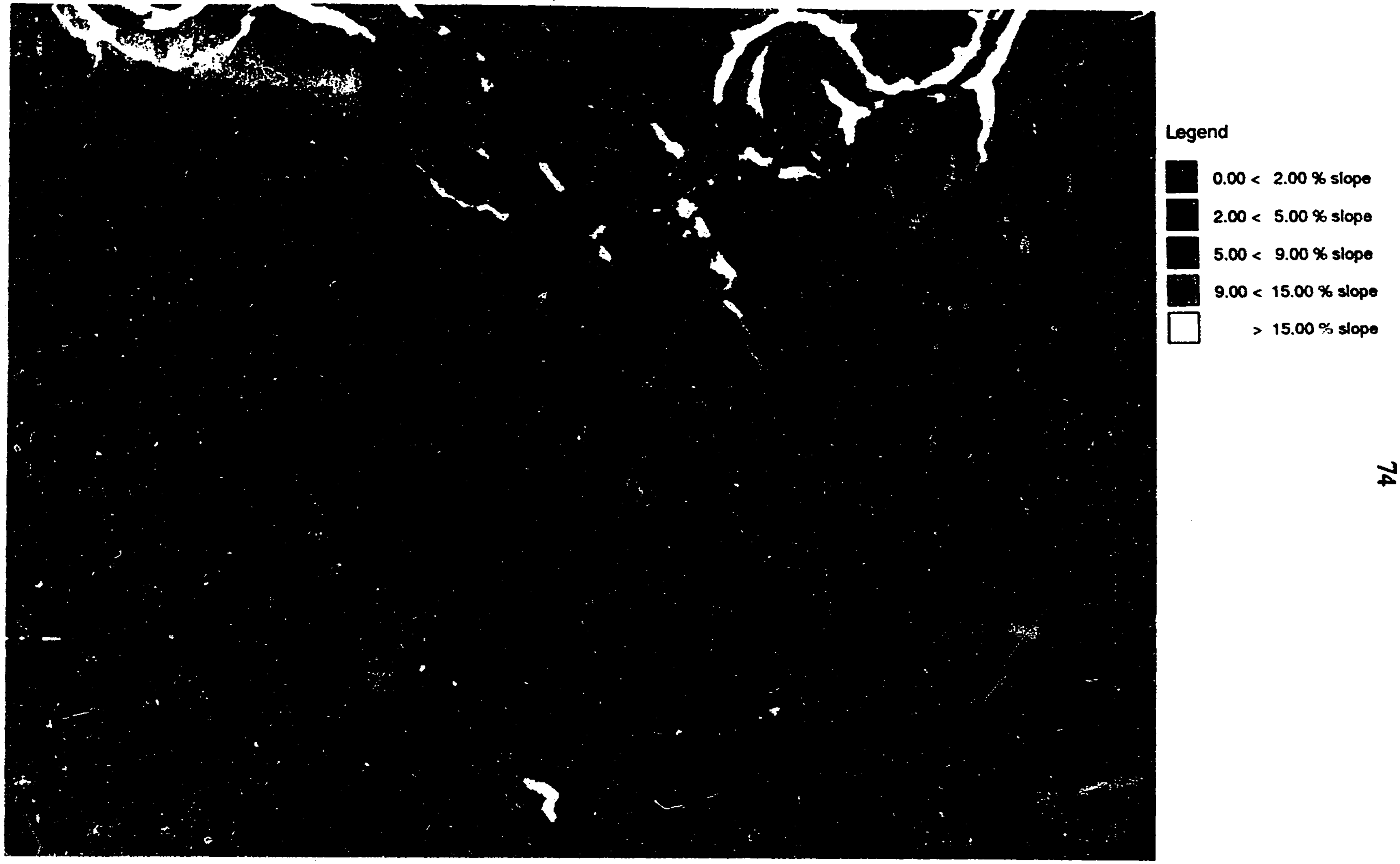


Figure 5.6. Slope gradient model, modal filter derived for a convolved 11x11 neighbourhood

Within areas of high spatial variability, the homogeneity of landform units was improved on the filtered slope gradient model map over the original heterogeneous classed grid cell pattern of the original slope gradient model. But the filtering process did not produce the preferred large areas of homogeneous units mapped in the County of St.Paul soil survey. For example, the County of St. Paul soil landform units *hummocky(9-15%)* and *hummocky(>15%)* could not be differentiated on the filtered slope gradient model map because the areal extent of units of high slope gradient class values was reduced. Both landform units, *hummocky(9-15%)* and *hummocky(>15%)*, are represented on the filtered slope gradient model map by a mixture of units of 5 to 15 percent slope.

5.4.3 Filtered Curvature Map

The generation of a filtered curvature map is only indirectly related to the objective of this research because curvature does not exist as a quantitative modifier on the County of St.Paul soil map or on the Sand River surficial geology map. But as described in the previous chapter, curvature is of importance for the determination of drainage lines, the location of poorly drained depressions, and the interpretation of landform patterns. The curvature map filtered for a convolved 5x5 neighbourhood (Figure 5.7) was compared with the original classed curvature map. The noise on the unfiltered curvature map, which is a consequence of higher order derivatives (Burrough, 1986), was substantially reduced on the filtered curvature map. The main drainage lines, such as the St. Lina Creek, emerge as prominent features on the filtered map because noise is no longer interfering with the more pronounced drainage network. Consequently, differences between linear and nonlinear channel and ridge networks between the *hummocky* and *ridged* to *rolling* landform types is enhanced and more clearly visible.

5.5 Summary and Future Research Considerations

The generation of the local relief map as well as the filtered slope gradient and downslope curvature model maps was based on context dependent neighbourhood operators. An attempt was made to determine the neighbourhood sizes based on texture and grain analysis. Grain analysis of low relief landforms using relief/area curves, a method described by Pike *et al.* (1989), did not present any *knick* within the selected neighbourhood size range of up to 475m. The

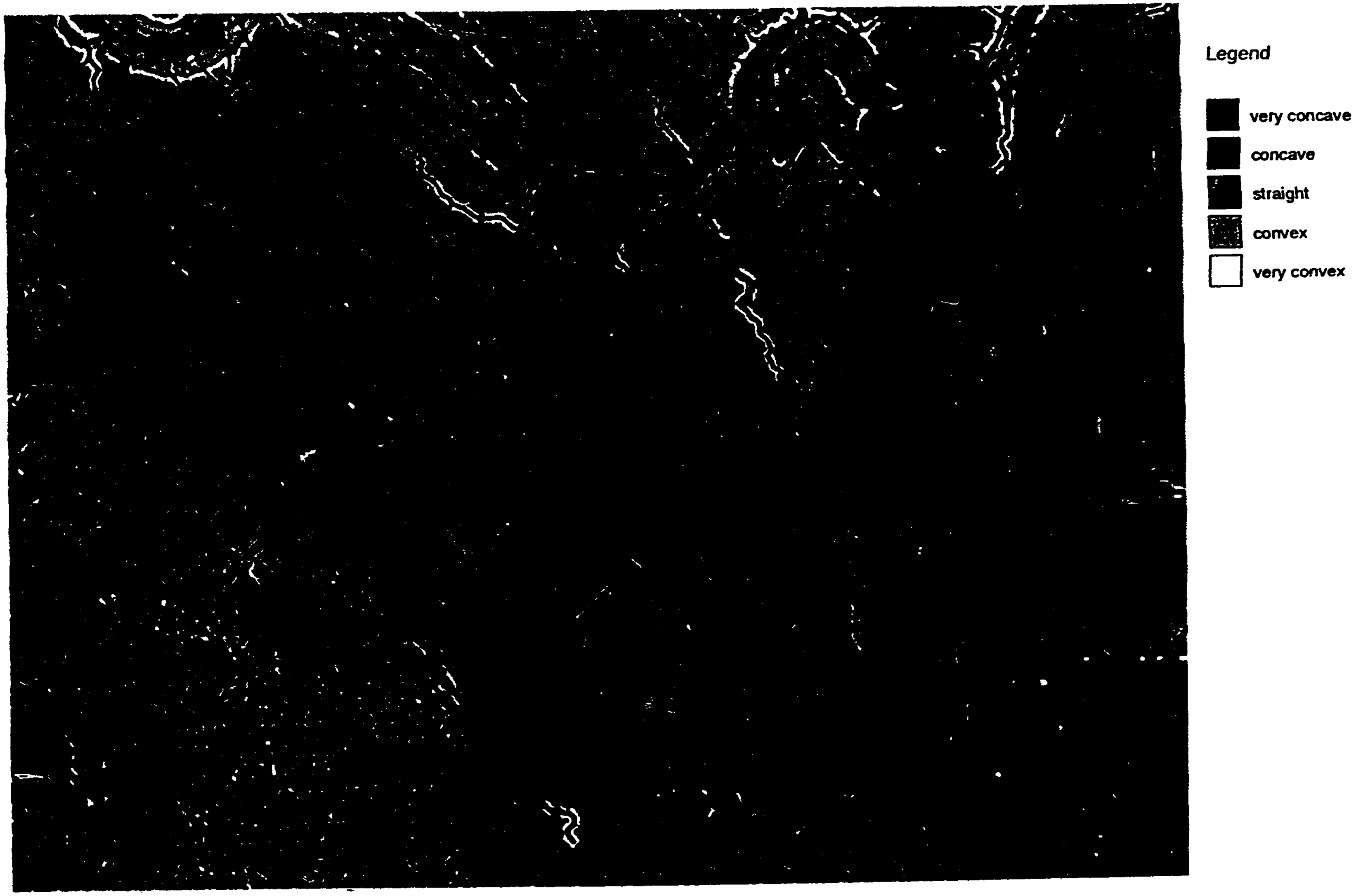


Figure 5.7. Downslope curvature model, modal filter derived for a convolved 5x5 neighbourhood

neighbourhood size was finally selected in accordance with an accurate representation of the local relief class limits as shown on the Sand River geology map. However, the selected neighbourhood sizes were much smaller than those derived according to texture analysis of slope gradient. This result contradicts the accepted definition in the literature that local relief represents the vertical variation of the long wavelengths, whereas texture represents the smaller wavelengths. Consequently, it was assumed that the local relief class limits defined by Andriashek and Fenton (1989) for the Sand River surficial geology map were either underestimated or that further research is needed to analyse the effects of grain analysis on low relief landforms. As long as the area over which local relief is derived, cannot be defined more accurately, it is recommended that slope gradient instead of local relief is used as a quantitative modifier in landform classification.

In this research, the determination of neighbourhood sizes for automated landform mapping based on relative variance has been implemented for the first time. The use of relative variance has the advantage of being a relative measure of homogeneity for which a predetermined threshold is provided by the logical break point of 0.5 relative variance representing equal values for within and between unit variance. However, the variation of relative variance between the different landform units causes difficulties in selecting a fixed neighbourhood size for mapping an entire study area. As a consequence, neighbourhood sizes determined according to relative variance can only act as a guideline within which the neighbourhood size for filtering can be specified. The final selection of the neighbourhood size is a trade-off between accuracy, with limits determined by texture or grain analysis, and simplicity judged by visual inspection. The ultimate decision, as to which neighbourhood size to select, is left to the analyst considering the objective of the mapping project and the overall desired impression of the map. Additionally, the varying relative variances and relief/area curves for different landform types of varying roughness suggest that the application of a flexible neighbourhood size should be implemented instead of a fixed neighbourhood size. Methods of image segmentation considering landform variation are discussed in chapter 7.

The application of a modal filtering technique greatly improves the readability of the slope gradient and curvature maps. The application of the modal filtering technique has the advantage over the use of the majority filtering technique in that the former generates a ratio scale data set while it uses the majority concept for filtering classed data sets. The ratio scale data set represents data value variations within class limits and does not generalize the data to be represented by one class value only. As a result, the filtered ratio scale data set can be used in parametric analysis.

Comparisons of the local relief and slope gradient model maps with the Sand River surficial geology map and the County of St. Paul soil map revealed that the areal extent of the derived homogeneous units and the morphometric class values is comparable between the maps in spite of overestimation of slope gradient class values on the County of St. Paul soil survey map. The results of landform mapping using DTMs and neighbourhood processing functions, described to this point in the thesis, have so far been assessed qualitatively, based solely on image comparison. Before the effectiveness of DTMs and neighbourhood processing functions in automated landform mapping can be properly evaluated, the models must also be interpreted quantitatively using descriptive statistics. Such a statistical analysis is the focus of the next chapter.

6. Quantitative Analysis of Soil and Geology Landform Classifications

To provide comparable landform category definitions for Canadian soil and geology survey maps, the Canadian System of Soil Classification (E.C.S.S., 1987a) adopted many aspects of the Terrain Classification System used by the Canadian Geology Survey (Howes & Kenk, 1988; Fulton *et al*, 1974). As a result, the definitions of surface expression provided by the Canadian System of Soil Classification and the Terrain Classification System overlap substantially (Table A1.1). Despite the attempt to provide comparable landform classifications, the two landform classifications used in the County of St. Paul soil survey (Brierley *et al*, 1990) and the Sand River surficial geology map (Fenton and Andriashek, 1983), vary not only according to surface expression definitions but also in the use of morphometric modifiers (Table A1.3 and A1.4). As a result, the location and areal extent of the individual landform units differ between the two surveys; aspects of these differences have been examined previously in Chapter 4 and 5. The differences between the two classifications are related to a lack of detail, and the exact definition of surface expression, because the classification is not based on a parametric system, and is the direct result of the subjectivity inherent in the photointerpretation process.

Similar methodological deficiencies also apply to the descriptive comparison of surface expression definitions as listed in Tables A1.3 to A1.4 and to the visual comparison of digital terrain model (DTM) maps, and soil and geology landform maps as described in Chapter 4 (Table 4.1) and 5. To avoid the subjectivity of such a qualitative analysis, a two-step quantitative analysis is presented in this chapter. First, landform categories are defined objectively on the basis of statistical measures derived from DTM distributions of local relief, slope gradient and downslope curvature; and, second, landform categories are statistically compared by testing the similarity of DTM distributions between the individual landform categories.

The chapter is divided into three sections. In the first section, the general suitability of DTM distributions to accurately represent landform categories and to discriminate between landform categories is examined. A second section involves the quantitative analysis of soil landform categories according to morphometric characteristics, and according to differences and similarities between DTM distributions. The same analysis is implemented to characterize and compare the geology categories. In a third section, the correspondence between geology and soil landform categories is statistically analysed according to areal overlap of the individual categories, as well as similarity and differences between DTM distributions. The detail of the statistical analysis was designed to provide the basis for redefining the description of landform categories and to refine the selection of rigid landform parameter definitions as anticipated by the E.C.S.S. (1987a) for future landform classifications.

6.1 Statistical Methods

The quantitative analysis implemented in this research is based on the concept of geometric signature defined by Pike (1988) as a set of measurements that describes topographic form precisely enough to distinguish geomorphologically disparate landforms. The statistical measurements are derived from morphometric variable distributions[6.1] represented by DTMs of local relief, slope gradient and downslope curvature and involve the overlay of soil and geology landform data sets not only with unclassed but also with classed DTMs. Classed DTMs have to be considered in this analysis because the soil and geology landform classifications are defined according to classed morphometric modifiers. The data used in the analysis appear in three different measurement scales: landform categories are represented as nominal scale data, classed DTMs as interval scale data, and unclassed DTMs as ratio scale data. Consequently, the statistical methods have to be selected not only according to the research objectives but also according to the data types.

Most of the quantitative landform analysis methods published in recent years rely on the availability of ratio scale data (Strahler, 1956; Gardiner, 1976; Speight, 1977; Evans, 1980; O'Neill and Mark, 1987; Pike, 1988; Pennock *et al.*, 1987; Carrara, 1983). For example, first order statistics, based on first moment and second moment measurements of morphometric variable distributions, such as mean and variance, were used to summarize, compare, and evaluate landform characteristics of different landform and physiographic regions (Evans, 1980; Pike and Thelin, 1989). For the analysis of interval and nominal scale data, however, nonparametric

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[6.1] The term *morphometric variable distribution* is used whenever general morphometric characteristics of landform categories are described whereas the term *DTM distribution* has the same meaning as morphometric variable distribution but refers in this thesis specifically to the characteristics derived from the DTM distributions of local relief, slope gradient and downslope curvature.

methods must be implemented. Histograms, cross-tabulations and nonparametric tests were used by several authors to describe and compare different landform categories (Gregory and Brown, 1966; Horvarth *et al.*, 1987, Westerveld *et al.*, 1987; Dikau, 1990b; Onorati *et al.*, 1992).

In this research, both, parametric and nonparametric, methods were used to describe the morphometric characteristics of the individual landform categories. Nonparametric measurements in form of histograms and cross-tabulations were used to determine dominant and secondary morphometric classes for the individual landform categories. Such measurements have been used before by Horvath *et al.* (1987) to facilitate the mapping and description of soil units. Parametric measurements were used in the present research in the form of standardized ranges and coefficients of variance derived from unclassed DTM distributions. Finally, the landform categories were ranked according to magnitude and variance of local relief, slope gradient and downslope curvature, as used by Pike (1988) to differentiate between soft and hard landform types affected by landslides. All of these statistical measurements were carried out to characterize the landform categories more accurately and more extensively than the dominant class modifier of local relief and slope gradient used currently in geology and soil landform classifications.

The second group of statistical methods used in this study evaluated the possibility of discriminating between landform categories on the basis of DTM distributions. Several multivariate analysis techniques have been used to differentiate between landform categories, including an indexing system based on first moment and second moment measurements of altitude, slope gradient and curvature distributions (Pike, 1988), F-tests to determine the discriminatory power of factor scores derived from a diversity of morphometric variables (Gardiner, 1976), and canonical (Pennock *et al.*, 1987) and stepwise discriminant analyses (Carrara, 1983) used to select landform attributes relevant for landform analysis. While all of these analytical techniques use frequency distributions of several samples representing the same landform category, this study focuses on the analysis of one frequency distribution which represents the entire landform category.

Differences and similarities between the morphometric variable distributions of the individual landform categories can be examined through the use of statistical tests. A nonparametric test, the Chi-square-test, was used by Westerveld *et al.* (1984) to compare ecological land units based on nominal and interval scale data.

The test, however, is meaningless when the class frequencies approach zero (Siegel, 1956). This phenomenon occurred in this research for the morphometric classes of several landform categories. Strahler (1956) faced the same problem when he used the Chi-square-test to compare differences between slope gradient distributions of different landscapes. To circumvent the problem of zero frequency counts, Strahler rearranged the limits of the classes so they contained at least 5 percent of the data distribution. For this study, the Chi-square-test still had to be rejected because the class limits are fixed, imposed by the geology (Andriashek and Fenton, 1989) and soil survey classifications (Brierley *et al.*, 1990).

The same principles, however, used by Westerveld *et al.* (1987) to compare the similarities and differences between landform categories were applied in this study by using a parametric F-test instead of the nonparametric Chi-square-test. F-tests have been used to compare variances of two different distributions (Davis, 1986) and can be applied here because the morphometric variables are also expressed as ratio scale data. The F-test was chosen over other tests because the F-test is not as affected by skewness and small sample sizes as other tests. The F-test, as applied in this thesis, compares the variances of each individual DTM distribution of local relief, slope gradient, and downslope curvature for every landform category combination within the geology classification, within the soil classification, and between the two classifications. The null hypothesis for these tests states that the variances of the morphometric variable distributions between two landform categories are the same and that the samples are derived from the same overall distribution at a significance level of 1 percent (Davis, 1986).

Finally, the relative variance was used to determine which DTM distribution best represents the landform categories as homogeneous units. The measure of homogeneity assumes that the morphometric distribution variance within the landform categories is less than the variance between the landform categories (described in Chapter 5). The relative variance is often used to test the accuracy and uniformity of map unit polygons in soil and geomorphology surveys (Beckett and Burrough, 1971; Webster and Beckett, 1971; Van Zuidam, 1986).

6.2 Morphometric Variable Selection

The morphometric variables represented by the DTM distributions of local relief, slope gradient and downslope curvature selected for the statistical analysis are the same as the ones used in previous chapters (Chapter 4 and 5). However, the use of elevation and azimuth data is restricted because the frequency distribution of the variables were not derived for each landform unit individually but for the entire landform category.

Elevation is not directly considered in the analysis because the elevation magnitude might vary from unit to unit within the same landform category. The resulting elevation range for the entire category might not represent the range within a unit but rather between units and would distort the elevation range for the entire landform category. For this reason, elevation was replaced in this research by local relief which measures the range of elevation over a neighbourhood as described in Chapter 5.

A similar problem affects the azimuth data. Azimuth distributions are used to differentiate between *inclined*, *ridged* and *hummocky* landform categories. *Inclined* landforms are unimodal, *ridged* landforms are bimodal whereas *hummocky* and most other landforms are multimodal. If azimuth values differ between two landform units within the same category, unimodality, bimodality or multimodality is not present in the overall frequency distribution of the landform category. Secondly, the statistical analysis of azimuth data is more complex as a result of the circular nature of the data (Davis, 1986). In this research, modality of azimuth data was derived from the visual inspection of azimuth histograms. The modality was used only to make a distinction between *hummocky*, *inclined* and *ridged* landform units if the graphical display of the classed data distribution permitted.

The frequency distributions of the DTMs were determined for unclassed and classed data sets. DTMs of local relief, slope gradient and downslope curvature were categorized according to the class limits used in Chapter 4 and 5 (Table A1.4 and A1.5). The azimuth distribution was divided into eight classes each associated with one of the eight cardinal compass points. A ninth class was added for slopes of less than 0.5 percent slope gradient (flat).

6.3 Overall Statistical Analysis of Morphometric Variables

6.3.1 Representation of Statistical Measures

The overall statistical analysis of morphometric variables represented by DTM distributions of local relief, slope gradient, and downslope curvature was used to determine the suitability of various DTMs to accurately represent the morphometric modifiers of the landform classifications and to discriminate between landform categories of the soil and geology classification. The following DTMs were analysed; local relief derived from convolved 3x3 to 11x11 neighbourhoods, slope gradient and filtered slope gradient derived from convolved 7x7 to 13x13 neighbourhoods, and downslope curvature and filtered downslope curvature derived from a convolved 5x5 neighbourhood. For the statistical analysis the following measurements were used (Table 6.1 and 6.2):

1. The measure of percent correspondence presents the percent overlap between the morphometric modifier classes associated with the landform categories and the corresponding DTM classes. This measurement was used to determine how accurately the morphometric modifiers were represented by corresponding DTM classes. The percent correspondence measure is listed only for those DTMs which coincide with the morphometric modifiers of the landform categories (local relief for geology landform categories and slope gradient for soil landform categories).
2. The overall correspondence of landform categories with dominant DTM classes is presented as a measure of percent dominant class overlap. The dominant class overlap determines how definite a landform category is associated with one DTM class only.
3. Relative variance specifies the homogeneity of DTM distributions within landform categories. As stated in Chapter 5, the relative variance was derived from the ratio of the pooled within landform category variance and the total variance for each DTM distribution. If the relative variance exceeded a value of 0.5, the variance between the categories was smaller than within the categories and the DTM did not represent the landform categories as homogeneous units.
4. The percent discriminatory power determines how well each DTM distribution discriminates between landform categories according to the results of the F-test given in appendix 2 (Figure A2.2.1 to A2.2.3 for the soil classification and Figure A2.4.1 to A2.4.3 for the geology classification). The discriminatory power was derived by counting the number of times the DTM distributions of two landform categories were not similar according to a 99 percent significance level and then by dividing this count by the number of landform category combinations (105 for the 15 soil landform categories and 190 for the 20 geology landform categories). The measure of discriminatory power was used by Westerveld *et al.* (1984) to test the ability of morphometric variables for the differentiation of landform categories.

6.3.2 Results

The statistical measures shown in Table 6.1 and 6.2 were used to determine which DTM distribution, local relief, slope gradient, or downslope curvature, represented the landform categories most accurately. Furthermore, the measures were used to determine empirically the outcome of neighbourhood processing implemented in Chapter 5. According to the measure of percent correspondence, the local relief modifiers associated with the geology landform categories were most accurately represented by a classed local relief distribution derived for a convolved 7x7 neighbourhood. The neighbourhood size was the same size as that determined in Chapter 5 according to a qualitative assessment of the relief/area curve. All other statistical measures listed in Table 6.1 and 6.2 do not suggest a strong trend which would indicate an improvement or deterioration in local relief distribution accuracy for increasing or decreasing neighbourhood sizes.

The effect of the filtering process derived from neighbourhoods of increasing sizes was analysed using the slope gradient DTM distributions. The measure of correspondence decreases slightly for neighbourhoods of increasing sizes. All other statistical measurements show an improvement in accuracy for landform categories obtained from filtered DTM distributions. The increase of percent dominant class overlap for filtered DTM distributions derived from neighbourhoods of increasing sizes is related to the effect of modal filtering which reduces the number of cases for classes containing the smallest frequencies. This assimilation process reduces the variance within the landform categories reflected by a lower relative variance for filtered data sets. At the same time, the discriminatory power increases, which indicates that the ability of the DTM distributions to discriminate between the landform categories has improved. According to the percent discriminatory power, slope gradient distributions differentiate more accurately between landform categories than local relief distributions, whereas, according to the relative variance, local relief distributions portray landform categories as more homogeneous than slope gradient distributions. The higher relative variance of local relief distributions, however, may not be related to an improvement in accuracy but may be explained by an increase in the number of local relief classes greater than 10 meters for increasing neighbourhood sizes which decreases the within variance and consequently the relative variance. The increased frequencies found for local relief

Table 6.1. Statistical Measures Assessing the Suitability of Different DTM Distributions for Delineating Soil Landform Categories

DTM distributions	% correspondence	% dominant class overlap	relative variance	% discriminatory power[1]
Local relief(3x3)		58.26	0.6556	75.24
Local relief(5x5)		56.63	0.6103	77.14
Local relief(7x7)		59.01	0.5722	70.48
Local relief(9x9)		58.60	0.5449	62.86
Local relief(11x11)		61.31	0.5266	66.67
Slope gradient (SG)	25.02 55.76*	55.76	0.6653	75.24
Filtered SG(7x7)	24.69 53.55*	58.63	0.6528	82.86
Filtered SG(9x9)	24.29 54.09*	59.92	0.6349	84.76
Filtered SG(11x11)	23.92 54.69*	61.16	0.6202	85.71
Filtered SG(13x13)	23.39 54.83*	62.30	0.6074	85.71
Downslope curvature (DSC)			0.9810	80.95
Filtered DSC(5x5)			0.9659	89.52

[1] The percent discriminatory power is derived by counting the number of times, DTM distributions are not similar between two landform categories at a 99% significance level using an F-test, divided by the total number of possible landform category combinations which is 105 for the 15 soil landform categories. For individual F-test results see Figure A2.2.1 to A2.2.3

* % correct classification for one slope gradient class interval lower than assigned to the soil landform category

Table 6.2. Statistical Measures Assessing the Suitability of Different DTM Distributions for Delineating Geology Landform Categories

DTM distribution	% correspondence	% dominant class overlap	relative variance	% discriminatory power[1]
Local relief(3x3)	50.28	55.98	0.7217	69.47
Local rellief(5x5)	65.95	50.78	0.6919	68.42
Local relief(7x7)	69.14	55.67	0.6682	67.27
Local rellief(9x9)	67.10	55.48	0.6520	64.74
Local relief(11x11)	62.61	57.41	0.6418	63.68
Slope gradient (SG)		54.49	0.7308	68.42
Filtered SG(7x7)		55.86	0.7455	73.68
Filtered SG(9x9)		57.05	0.7418	73.68
Filtered SG(11x11)		57.78	0.7389	75.24
Filtered SG(13x13)		58.63	0.7373	79.47
Downslope curvature (DSC)			0.9899	74.21
Filtered DSC(5x5)			0.9892	74.74

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[1] The percent discriminatory power is derived by counting the number of times, DTM distributions are not similar between two landform categories at a 99% significance level using an F-test, divided by the total number of possible landform category combinations which is 190 for the 20 geology landform categories. For individual F-test results see Figure A2.4.1 to A2.4.3

classes greater than 10 meters, in turn, reduces the discriminatory power of the local relief distribution.

The measures of relative variance and percent discriminatory power are even more contradictory when comparing the downslope curvature distribution with the slope gradient and local relief distributions. According to the measure of discriminatory power, the downslope curvature distributions allow for a more accurate differentiation between landform categories than any other DTM distribution, whereas a very high relative variance indicates a low homogeneity of downslope curvature distribution within the landform categories. The low homogeneity indicates a high variance within the landform categories which is caused by a high kurtosis. The high kurtosis, which is expressed by a high concentration of values around zero, is particularly a result of downslope curvature being a second order derivative of elevation.

Furthermore, the variance of the filtered downslope curvature values within the landform categories is overestimated; this is caused by the modal filtering process used in this research. In the modal filtering process, the lower and upper class limits were set very high to include the extreme values of the distribution. Consequently, the modal values of the very concave and very convex classes are disproportionally increased and decreased (see Chapter 5 for a description of the modal filtering methods) which causes the within landform category variance to be further increased for downslope curvature distributions. To a lesser degree, the overestimation of the extreme modal class values applies not only to the curvature DTMs but also to the upper class of the filtered slope gradient DTMs.

The calculation of percent dominant class overlap for dominant downslope curvature classes is meaningless because most landform categories are represented by straight slopes caused by the high concentration of values around zero. In addition, no percent correspondence was determined because curvature was not used as a morphometric modifier in the soil or the geology landform classification. Measures of the azimuth distributions are also not listed in Tables 6.1 and 6.2 because the landform categories are not described by a specific azimuth direction but according to varying azimuth modalities as described in section 6.2. The F-test and relative variance are not of any value for differentiating the modality status between landform categories because these tests compare the azimuth distribution variances instead of similarities in unimodality, bimodality, or multimodality between the landform categories.

According to the relative variance, no DTM distribution differentiates between the landform categories satisfactorily. The between category variance is greater in all cases than the within category variance, reflected by a higher than 0.5 relative variance. The relative variance, however, may be an inappropriate method to measure the homogeneity of the landform categories because too little is known about the application of relative variance in landform mapping (see Chapter 5). The chance, however, is greater that the landform maps are inaccurate because the delineation of the landform categories was also dependent on other than landform characteristics. Comparing the percent discriminatory power, the relative variance and the percent dominant class overlap of the soil and geology landform classifications, in some instances, the measurements vary more between the soil and geology landform classifications than between the DTM distributions. Consequently, the interpretation of surface expression and the use of morphometric modifiers, on which basis the landform categories were delineated in the soil and geology landform mapping projects, influence the result of the statistical analysis more than the differences between the DTM distributions. The following sections, therefore, analyse and discuss the accuracy of the soil and geology landform classifications in even greater detail.

6.4 Analysis of the Soil and the Geology Landform Classifications

6.4.1 Representation of Statistical Measures

Based on the digital overlay of the County of St.Paul soil landform classification and the Sand River geology landform classification with DTM distributions of local relief, slope gradient, azimuth and downslope curvature, the following statistical measures were derived represented in various diagrams and tables:

1. Classed frequency distributions of local relief, slope gradient, downslope curvature and azimuth derived for each landform category of the geology and soil classification are presented as histograms (Figure A2.1.1 to A2.1.15 for soil landform categories and Figure A2.3.1 to A2.3.20 for geology landform categories). The frequency distributions of the original DTMs and the filtered DTMs are considered in these histograms. The filtered slope gradient DTMs were derived from a convolved 11x11 neighbourhood (filt.sl.grad.(11x11)) and the filtered downslope curvature DTM from a convolved 5x5 neighbourhood

(filt.dsl.curv.(5x5)). Local relief was determined by the calculation of ranges from convolved 3x3 (local relief (3x3)) and 7x7 neighbourhoods.

2. The dominant and secondary DTM classes for local relief, slope gradient and downslope curvature and the associated percent frequencies were derived from the histograms and are presented in Table 6.3.1 to 6.3.3 for soil landform categories and Table 6.5.1 to 6.5.3 for geology landform categories. The dominant DTM class is of special importance because the notation of the quantitative modifier used in the County of St.Paul soil survey is based on the determination of the dominant slope gradient class (Brierley *et al.*, 1990).
3. The standardized range containing 50 percent of a morphometric variable distribution was calculated for each landform category by adding plus and minus 0.67 standard deviation units to the mean. The standardized range is used as another measure, which represents the majority of the morphometric distribution (50%), and can be used to replace the nonparametric modifier represented by the dominant class. The standardized range for curvature was not of great importance in the analysis because most categories are represented by straight slopes caused by a high concentration of values around zero as described in section 6.3.2. However, the range between the lower and upper limits indicates the variability of the land surface.
4. The coefficient of variance was calculated as a ratio of the standard deviation and the mean, and was used by Pike and Thelin (1989) to represent topographic homogeneity within physiographic regions. This measure was used in this study to indicate the comparability of two landform categories not only with respect to their variances as shown by the F-test but to recognize differences between the mean and the variance of the DTM distributions within the landform category. A coefficient of variance above 1.0 suggests that the standard deviation is higher than the mean and the landform category is considered to be heterogeneous. A coefficient of variance of less than 1.0 indicates that the standard deviation is less than the mean and the landform category is most likely to be homogeneous. The calculation of a coefficient of variance from the downslope curvature distribution is meaningless because downslope curvature distributions contain a high frequency of zero curvature values resulting in a mean value of or near zero.
5. The landform units were ranked according to a method used by Pike (1988) to differentiate between hard and soft terrain types affected by landslides. The rank was used in this study to provide another measure for differentiating between

landform categories of the same dominant class and similar variance. A rank of 1 was assigned to the landform categories of lowest relief and slope gradient magnitude represented by the highest frequency of 0 to 1 meter local relief and 0 to 2 percent slope gradient. The ranks of local relief and slope gradient variance were assigned according to increasing variance values and indicate the degree of landform roughness within a landform category. The rank for downslope curvature, which was determined according to the highest percent of straight slopes, is closely related to the rank of slope gradient variance because the standard deviation of slope gradient is simply another expression of the degree of curvature (Evans, 1972). The statistical measures listed in points 2 to 5 are summarized in a series of tables (Table 6.3.1 to 6.3.3 for the soil landform categories and Table 6.5.1 to 6.5.3 for the geology landform categories).

6. The measure of similarity between landform categories was determined for those categories which had the same morphometric variable distributions at a 99 percent significance level (Table 6.4 for soil landform categories and table 6.6 for geology landform categories). The measure of morphometric variable distribution similarity is based on a comparison of variances using the F-test. The F-test results for local relief(7x7), slope gradient and downslope curvature are listed in appendix 2 for F-values at a significance level of less than 1 percent or 1.70 (Table A2.1.1 to A2.1.3 for soil landform categories and Table A2.2.1 to A2.2.3 for geology landform categories). The measure of similarity was derived by counting the number of times morphometric variable distributions were not significantly different between two landform categories implemented for every combination of landform categories. For example, a count of 3 indicates that the distributions of local relief(7x7), slope gradient and downslope curvature are not significantly different between two landform categories. Westerveld *et al.* (1984) used this count of similarity as a measure to determine correspondences between landform categories.

6.4.2 Analysis of the County of St.Paul Soil Landform Classification

The measure of percent correspondence (Table 6.1) represents a very low overlap of only 25.02% between slope gradient classes associated with soil landform categories and the corresponding slope gradient DTM classes whereas the value of 55.76% dominant class overlap (Table 6.1) is more than twice as high as the value of percent correspondence. These two measures differ because the corresponding slope gradient DTM classes are generally one if not two class intervals below those estimated by the soil survey for the quantitative modifier (Table 6.3.2). For this reason, the percent correspondence is calculated a second time for slope gradient DTM class limits one interval below that assigned to the soil landform category (Table 6.1). The percent correspondence of slope gradient for soil landform categories increases from 25.02% to 57.70%. This result confirms the observation made in Chapter 4 and 5 that slope gradient was overestimated on the County of St.Paul soil survey map.

The characteristics of the individual landform categories can be best interpreted from the histograms (Figure A2.1.1 to A2.1.15) and the statistical measurements given in Table 6.3.1 for local relief distributions, in Table 6.3.2 for slope gradient distributions, and in Table 6.3.3 for downslope curvature distributions. Measures of morphometric distribution similarities between the landform categories according to F-test results for local relief, slope gradient and downslope curvature are listed in Table 6.4 (for single variable listings see Figures A2.2.1 to A2.2.3).

The landform category *lake* represents the flattest of all landform categories in the study area and has the highest percentage of 0 to 1 meter local relief and 0 to 2 percent slope gradient which is also reflected by a high frequency of straight slopes and the lowest rank of local relief and slope gradient magnitude. The landform categories *level(0-2%)*, *undulating(0-5%)*, *undulating(2-5%)* and *hummocky(5-15%)* are of slightly higher relief than category *lake* and are similar according to the rank, dominant class and standardized range. While only the landform categories *level(0-2%)* and *undulating(2-5%)* are drawn from the same population according to the F-test results (Table 6.4), the category *hummocky(5-15%)* is not significantly different from the category *lake*. The two categories, *lake* and *hummocky(5-15%)*, can only be differentiated according to the standardized range which is higher for *hummocky(5-15%)* than for *lake* caused by a higher mean value of the landform category *hummocky(5-15%)*. This discrepancy between the mean and the standard deviation between the two landform categories is expressed by different coefficients of variance. *Lake* has a coefficient of variance twice as high as *hummocky(5-15%)*. The higher than expected variance of the category *lake* is probably related to an increase of slope gradient and local relief values at the margins of lakes which causes the category *lake* to appear as rough as *hummocky(5-15%)*. According to the

Table 6.3.1. Statistical Measures Describing Local Relief Characteristics for Soil Landform Categories

Local relief(7x7) (meters)

Landform categories (% of total area)	Dominant & 2.class	%FQ[1]	Rank mag[2]	Standardized range LL[3]	Standardized range UL[4]	Rank var[5]	CV[6]
Lake	0-1	(55.35)	(1)	0.18	3.00	(3)	1.32
(2.33)	1-3	(29.12)					
Level(0-2%)	1-3	(39.86)	(2)	0.74	4.39	(6)	1.06
(10.74)	0-1	(31.90)					
Level(0-10%)	3-10	(53.31)	(8)	3.13	10.26	(14)	0.80
(2.31)	1-3	(24.35)					
Undulating(0-5%)	1-3	(47.91)	(4)	1.48	4.27	(2)	0.73
(0.49)	3-10	(36.47)					
Undulating(2-5%)	1-3	(50.34)	(5)	1.36	4.99	(4)	0.85
(22.57)	3-10	(36.03)					
Dissected(>5%)	>10	(98.14)	(15)	16.25	23.18	(12)	0.26
(0.13)	3-10	(1.86)					
Dissected(>10%)	>10	(86.15)	(14)	13.45	23.15	(15)	0.40
(2.87)	3-10	(13.39)					
Hum-Inclined(>9%)	>10	(55.81)	(13)	8.09	14.36	(10)	0.42
(0.40)	3-10	(43.93)					
Hum-Inclined(>15%)	3-10	(51.68)	(11)	6.28	12.88	(11)	0.51
(0.70)	>10	(41.11)					
Hum-Ridged(5-9%)	3-10	(69.03)	(6)	3.07	6.71	(5)	0.56
(8.18)	1-3	(24.59)					
Hum-Ridged(9-15%)	3-10	(63.58)	(9)	4.47	9.25	(8)	0.52
(1.43)	>10	(21.64)					
Hummocky(5-9%)	3-10	(65.23)	(7)	3.18	7.57	(7)	0.61
(19.81)	1-3	(21.72)					
Hummocky(9-15%)	3-10	(65.23)	(10)	4.73	10.51	(9)	0.57
(19.37)	>10	(23.99)					
Hummocky(>15%)	3-10	(53.31)	(12)	6.46	13.47	(13)	0.52
(8.45)	>10	(42.61)					
Hummocky(5-15%)	1-3	(68.49)	(3)	1.57	4.09	(1)	0.66
(0.22)	3-10	(26.45)					

[1] frequency, [2] magnitude, [3] lower limit, [4] upper limit, [5] variance, [6] coefficient of variance

Table 6.3.2. Statistical Measures Describing Slope Gradient Characteristics for Soil Landform Categories

	Slope gradient (percent)						
	Dominant & 2.Class %FQ[1]		Rank mag[2]	Standardized range		Rank var[5]	CV[6]
Landform categories				LL[3]	UL[4]		
Lake	0-2	(90.95)	(1)	0.00	1.62	(2)	1.69
	2-5	(7.02)					
Level(0-2%)	0-2	(80.43)	(3)	0.19	2.51	(4)	1.28
	2-5	(15.27)					
Level(0-10%)	0-2	(40.18)	(8)	1.27	6.38	(13)	1.00
	2-5	(35.49)					
Undulating(0-5%)	0-2	(74.00	(4)	0.72	2.15	(1)	0.75
	2-5	(25.56)					
Undulating(2-5%)	0-2	(72.46)	(5)	0.54	2.89	(5)	1.02
	2-5	(23.78)					
Dissected(>5%)	9-15	(36.88)	(15)	7.47	15.95	(15)	0.54
	15-30	(29.24)					
Dissected(>10%)	9-15	(42.50)	(14)	6.76	13.25	(14)	0.48
	5-9	(26.13)					
Hum-Inclined(>9%)	5-9	(42.25)	(13)	4.21	8.52	(10)	0.50
	2-5	(29.90)					
Hum-Inclined(>15%)	2-5	(33.56)	(11)	3.05	7.74	(11)	0.65
	5-9	(32.89)					
Hum-Ridged(5-9%)	2-5	(48.89)	(6)	1.45	3.88	(6)	0.68
	0-2	(41.58)					
Hum-Ridged(9-15%)	2-5	(44.26)	(9)	2.12	5.05	(8)	0.61
	0-2	(28.69)					
Hummocky(5-9%)	2-5	(47.90)	(7)	1.47	4.39	(7)	0.75
	0-2	(38.89)					
Hummocky(9-15%)	2-5	(43.08)	(10)	2.21	6.28	(9)	0.71
	5-9	(25.94)					
Hummocky(>15%)	2-5	(35.94)	(12)	3.11	8.20	(12)	0.67
	5-9	(32.90)					
Hummocky(5-15%)	0-2	(82.05)	(2)	0.59	2.36	(3)	0.89
	2-5	(14.58)					

[1] frequency, [2] magnitude, [3] lower limit, [4] upper limit, [5] variance, [6] coefficient of variance

Table 6.3.3. Statistical Measures Describing Downslope Curvature Characteristics for Soil Landform Categories

	Downslope Curvature (percent/25meters)					
				Standardized range		
Landform categories	Dominant & 2.class	%FQ[1]	Rank mag[2]	LL[3]	UL[4]	Rank var[5]
Lake	str* cv*	(76.85) (18.69)	(2)	-0.73	0.30*	(3)
Level(0-2%)	str* cv*	(69.82) (23.09)	(5)	-0.86	0.35*	(4)
Level(0-10%)	cv* str*	(45.18) (30.20)	(10)	-3.05	1.01*	(14)
Undulating(0-5%)	str* cv*	(84.72) (12.58)	(1)	-0.35	0.07*	(1)
Undulating(2-5%)	str* cx*	(71.33) (14.07)	(3)	-0.73	0.76*	(5)
Dissected(>5%)	vcv* cv*	(45.87) (31.92)	(15)	-7.43	-0.35*	(15)
Dissected(>10%)	cv* cx*	(34.10) (33.36)	(14)	-2.32	1.53*	(13)
Hum-Inclined(>9%)	cv* cx*	(43.22) (31.61)	(13)	-1.54	1.31*	(11)
Hum-Inclined(>15%)	cv* cx*	(42.42) (27.26)	(11)	-1.64	1.11*	(10)
Hum-Ridged(5-9%)	str* cv*	(55.57) (21.82)	(6)	-0.78	0.75*	(7)
Hum-Ridged(9-15%)	str* cx*	(43.83) (29.19)	(8)	-0.72	0.80*	(6)
Hummocky(5-9%)	str* cx*	(52.35) (25.04)	(7)	-0.81	0.86*	(8)
Hummocky(9-15%)	str* cv*	(34.73) (32.36)	(9)	-1.36	1.24*	(9)
Hummocky(>15%)	cv* cx*	(37.38) (30.15)	(12)	-1.92	1.58*	(12)
Hummocky(5-15%)	str* cv*	(70.60) (15.90)	(4)	-0.53	0.46*	(2)

[1] frequency, [2] magnitude, [3] lower limit, [4] upper limit, [5] variance

Table 6.4. Measures of Morphometric Distribution Similarities between Soil Landform Categories

Soil categories	1 Lake	2 Level	3 Level	4 Undul	5 Undul	6 Diss	7 Diss	8 Huln	9 Huln	10 HuRi	11 HuRi	12 Hum	13 Hum	14 Hum	15 Hum
1 Lake	3														
2 Level(0-2%)	2	3													
3 Level(0-10%			3												
4 Undulating(0-5%)	2			3											
5 Undulating(2-5%)	1	3		1	3										
6 Dissected(>5%)			1			3									
7 Dissected(>10%)			2			1	3								
8 Hum-Inclined(>9%)			2			1		3							
9 Hum-Inclined(>15%)			2			1		3	3						
10 Hum-Ridged(5-9%)	1	3		1	3					3					
11 Hum-Ridged(9-15%)		2			2					2	3				
12 Hummocky(5-9%)		2			3					3	3	3			
13 Hummocky(9-15%)			2			1		3	3		1		3		
14 Hummocky(>15%)			3			1	2	3	3				2	3	
15 Hummocky(5-15%)	3	1		2											3

A measure of 3 indicates that two categories are similar for all morphometric distributions(local relief, slope gradient and downslope curvature) at a 1% significance level using an F-test. For individual F-test results see Figure A2.2.1 to A2.2.3

standardized range, category *hummocky(5-15%)* resembles more closely the categories *level(0-2%)* and *undulating* than any of the *hummocky* categories. *Hummocky(5-15%)* should therefore be relabelled as *undulating* or *level(0-2%).*

Contrary to the results of the F-test, which indicate no significant difference between the categories *undulating(2-5%), hummocky(5-9%)* and *hummocky-ridged(5-9%),* only the categories *hummocky(5-9%)* and *hummocky-ridged(5-9%)* are alike according to the statistical measures presented in Table 6.3.1 to 6.3.3. The categories *hummocky(5-9%)* and *hummocky-ridged(5-9%)* can only be differentiated using the azimuth distribution (Figure A2.1.10 to A2.1.12). *Hummocky(5-9%)* should be represented by azimuthal multimodality, and *hummocky-ridged(5-9%)* by azimuthal bimodality. Based on visual inspection of the azimuth histograms, *hummocky(5-9%)* and *hummocky-ridged(5-9%)* are both represented by a slight bimodality whereas more than 50% of the category *hummocky-ridged(9-15%)* consist of NE and SW, and E and W facing slopes. These azimuth directions correspond with the direction of the flutings in the study area (Andriashek and Fenton, 1989). The NE-SW striking ridges can be associated with the direction of the Lac La Biche ice lobe/event trending from northwest to southeast and the E-W striking ridges with the direction of the Seibert ice lobe/event trending from north to south. Furthermore, the landform categories *hummocky(9-15%), hummocky(>15%), hummocky-inclined(>9%)* and *hummocky-inclined(>15%),* which are similar according to the distributions of local relief, slope gradient and downslope curvature (Table 6.4), should also be distinguishable on the basis of the azimuth distribution. *Hummocky-inclined* categories should be more unimodal than *hummocky* categories. According to the azimuth histograms (Figure A2.1.8 and 9, and Figure A2.1.13 and 14), only *hummocky-inclined(>15%)* portrays a slight bias towards unimodality.

The distinction made by the soil survey between several *hummocky, hummocky-inclined* and *hummocky-ridged* landform categories according to different slope gradient classes cannot be made according to the dominant slope class derived from the DTM distributions. For example, *hummocky(5-9%), hummocky(9-15%)* and *hummocky(>15%)* are all characterized by the same dominant slope gradient class of 2 to 5 percent slope (Table 6.3.2) The slope gradient class limits are of lower magnitude than the class limits associated with the landform categories of the soil survey as discussed in Chapter 5. Only, slope gradient histograms and standardized ranges reflect the increase of frequencies found going from lower to higher class values.

A reversal of slope gradient ranks exists between *hummocky-inclined(>9%)* and *hummocky-inclined(>15%)*. *Hummocky-inclined(>9%)*, the category with the less steep slope gradient modifier, is characterized by steeper DTM slope gradient values than *hummocky-inclined(>15%)*. This inconsistency may be explained by the location of the category *hummocky-inclined(>9%)* at the margin of the soil map. The morphometric variable distribution represented within the study area reflects only parts of the frequency distribution which may not be representative for the distribution of the entire landform category. This edge effect may also affect other categories especially of the geology classification.

The landform category *level(0-10%)* implies a surface expression of flat or nearly flat terrain. But, as described in Chapter 4, *level(0-10%)* represents the floodplains and creek valleys on the soil survey map. The ranks for magnitude and variance values for slope gradient, local relief and downslope curvature are consequently higher than expected for a *level* surface expression. For example, *level(0-10%)* has a rank of 8 for slope gradient magnitude whereas the rank of variance at 13 is the third highest of all 15 soil landform categories. The presence of floodplains with a high frequency of gentle slopes are responsible for the lower rank of slope gradient magnitude than slope gradient variance whereas the presence of the creek valleys is related to an increase of the variance rank. Furthermore, the surface expression of creeks is reflected by a higher percentage of concave than convex slopes as indicated in Table 6.3.3 and Figure A2.1.3.

Both *dissected* categories are associated with the roughest land surface in the study area located along the river valley walls. As a result, the *dissected* categories are represented by slope gradient and local relief magnitudes and variances of highest rank. The slope gradients are steeper for category *dissected(>5%)* than *dissected(>10%)*. The reversal between the actual steepness and the associated slope gradient modifier is not related to an edge effect as described for the two *hummocky-inclined* categories. To avoid confusion between the two *dissected* categories, both categories should be combined to form one category only.

In summary, the hierarchy of landform categories established by the soil survey according to slope gradient classes and variability of surface expression coincides generally with the ranks derived according to magnitude and variance of the slope gradient distributions. For some classes, ranks of slope gradient magnitude differ from ranks of slope gradient variance which suggests that not only the dominant class but also the variance has to be considered for the determination of the morphometric modifier class and class ranges. The standardized range fulfills this requirement and provides a more precise measure of majority slope gradient values than the dominant slope class. But as pointed out by O'Neill and Mark (1987), and Strahler (1956), the mean and therefore the standardized range is often higher than the mode because the slope gradient distributions show generally a positive skewness.

6.4.3 Analysis of the Sand River Geology Landform Classification

The local relief modifiers of the geology landform categories are for 69.14% of all cases correctly classified by the DTM classes of local relief(7x7) (Table 6.2). But only 55.67% of the landform categories are associated with a single corresponding dominant local relief DTM class. The percent of correspondence is higher than the percent dominant class overlap because the local relief modifiers extend over two class intervals for several landform categories. For example, *hummocky-rolling(1-10m)* covers the local relief classes 1 to 3 meters and 3 to 10 meters.

In the following section, the individual landform categories are characterized according to class frequency distributions presented as histograms (Figure A2.3.1 to A2.3.20), and the statistical measurements listed in Tables 6.5.1 to 6.5.3. Furthermore, the landform categories are compared according to measures of morphometric distribution similarities (Table 6.6, and for F-test results of the individual morphometric distributions see Figure A2.4.1 to A2.4.3). The landform categories of lowest relief, *lake*, is closely related to *flat-hummocky* and *flat-rolling* landform categories which is expressed by a high count of morphometric distribution similarities according to the F-test results (Table 6.6). But category *lake* does not show any resemblance with category *flat*, which, according to the definition of surface expression, is represented by a lower relief than associated with the categories *flat-hummocky* and *flat-rolling*. The statistical measures (Table 6.5.1 to 6.5.3) show that *flat* has a higher standardized range and a higher variance for all DTM distributions than *flat-hummocky* and *flat-rolling*. Furthermore, the F-test results indicate that *flat* is not significantly different from *rolling(1-3m)* and *ridged(3-10m)*. This inconsistency between the landform category label and the actual

Table 6.5.1. Statistical Measures Describing Local Relief Characteristics for Geology Landform Categories

Landform categories (% of total area)	Dominant & 2.class	%FQ[1]	Rank mag[2]	Local relief(7x7) (meters) Standardized range LL[3]	 UL[4]	Rank var[5]	CV[6]
Lake (1.81)	0-1 1-3	(55.99) (28.05)	(1)	0.18	3.00	(3)	1.32
Varied (5.48)	>10 3-10	(63.44) (28.05)	(18)	9.29	24.23	(20)	0.66
Terrace (0.66)	>10 3-10	(61.12) (26.47)	(17)	8.83	17.90	(16)	0.51
Flat (8.82)	1-3 0-1	(37.42) (30.17)	(2)	0.24	7.05	(12)	1.40
Flat-Hummocky(0-3m) (7.57)	1-3 0-1	(58.23) (25.39)	(3)	0.38	3.81	(3)	1.22
Flat-Rolling(0-3m) (1.73)	1-3 0-1	(66.13) (16.64)	(4)	1.16	2.99	(1)	0.66
Rolling(1-3m) (7.09)	1-3 3-10	(44.47) (29.08)	(5)	0.91	6.43	(7)	1.12
Rolling(3-10m) (11.68)	3-10 1-3	(49.01) (30.37)	(8)	2.31	9.40	(13)	0.90
Rolling(>10m) (2.26)	3-10 >10	(53.20) (43.38)	(13)	6.46	14.08	(14)	0.55
Hummocky(1-3m) (0.18)	>10 3-10	(49.12) (32.90)	(14)	5.93	15.25	(18)	0.66
Hummocky(3-10m) (0.20)	>10 3-10	(64.08) (35.35)	(19)	8.51	17.66	(17)	0.52
Humocky(>3m) (12.37)	3-10 >10	(61.96) (29.42)	(12)	5.32	10.97	(8)	0.52
Hum-Rolling(1-3m) (4.91)	1-3 3-10	(46.37) (32.52)	(6)	0.88	5.67	(5)	1.09
Hum-Rolling(1-10m) (22.98)	3-10 1-3	(61.60) (27.53)	(7)	2.64	7.26	(4)	0.70
Hum-Rolling(3-10m) (0.94)	>10 3-10	(50.41) (45.62)	(15)	7.27	15.13	(15)	0.52
Hum-Rolling(>3m) (0.25)	>10 3-10	(54.51) (44.32)	(16)	8.24	14.48	(10)	0.41
Hum-Rolling(>10m) (0.03)	>10 3-10	(82.89) (14.47)	(20)	12.33	23.90	(19)	0.48
Hum-Ridged(>3m) (2.85)	3-10 >10	(69.14) (23.02)	(11)	5.17	9.98	(6)	0.47
Ridged(3-10m) (0.14)	3-10 >10	(64.35) (22.68)	(10)	4.27	10.51	(11)	0.63
Ridge-Rolling(3-10m) (8.03)	3-10 1-3	(60.03) (25.65)	(9)	2.69	8.45	(9)	0.77

[1] frequency, [2] magnitude, [3] lower limit, [4] upper limit, [5] variance, [6] coefficient of variance

Table 6.5.2. Statistical Measures Describing Slope Gradient Characteristics for Geology Landform Categories

	Slope gradient (percent)						
				Standardized range			
Landform categories	Dominant & 2.class	%FQ[1]	Rank mag[2]	LL[3]	UL[4]	Rank var[5]	CV[6]
Lake	0-2	(90.20)	(2)	0.00	1.58	(2)	1.61
	2-5	(7.80)					
Varied	9-15	(29.76)	(19)	4.68	13.68	(19)	0.73
	2-5	(18.78)					
Terrace	2-5	(32.35)	(18)	3.81	10.28	(18)	0.68
	5-9	(30.10)					
Flat	0-2	(76.19)	(4)	0.00	3.84	(9)	1.58
	2-5	(14.62)					
Flat-Hummocky(0-3m)	0-2	(89.54)	(3)	0.13	2.18	(3)	1.33
	2-5	(9.38)					
Flat-Rolling(0-3m)	0-2	(91.61)	(1)	0.49	1.78	(1)	0.85
	2-5	(7.83)					
Rolling(1-3m)	0-2	(70.38)	(6)	0.34	3.69	(6)	1.24
	2-5	(20.30)					
Rolling(3-10m)	0-2	(48.85)	(7)	0.90	5.50	(13)	1.07
	2-5	(33.05)					
Rolling(>10m)	2-5	(38.22)	(13)	3.05	7.87	(15)	0.66
	5-9	(36.21)					
Hummocky(1-3m)	0-2	(27.75)	(14)	2.73	8.77	(16)	0.78
	2-5	(25.06)					
Hummocky(3-10m	5-9	(37.42)	(17)	3.93	10.39	(17)	0.67
	2-5	(30.28)					
Hummocky(>3m)	2-5	(40.62)	(12)	2.56	6.67	(11)	0.66
	5-9	(29.28)					
Hum-Rolling(1-3m)	0-2	(71.50)	(5)	0.25	3.42	(5)	1.29
	2-5	(22.82)					
Hum-Rolling(1-10m)	0-2	(45.55)	(8)	1.18	4.21	(4)	0.84
	1-5	(42.99)					
Hum-Rolling(3-10m)	5-9	(37.07)	(15)	3.62	8.35	(14)	0.59
	2-5	(33.14)					
Hum-Rolling(>3m)	5-9	(42.61)	(16)	4.00	8.41	(12)	0.53
	2-5	(33.43)					
Hum-Rolling(>10m)	15-30	(26.64)	(20)	4.61	17.59	(20)	0.87
	5-9	(21.38)					
Hum-Ridged(>3m)	2-5	(44.27)	(11)	2.43	6.19	(7)	0.65
	5-9	(26.74)					
Ridged(3-10m)	2-5	(42.25)	(10)	2.35	6.27	(8)	0.68
	5-9	(25.58)					
Ridge-Rolling(3-10m)	0-2	(43.00)	(9)	1.04	4.99	(9)	0.98
	2-5	(42.26)					

[1] frequency, [2] magnitude, [3] lower limit, [4] upper limit, [5] variance, [6] coefficient of variance

Table 6.5.3. Statistical Measures Describing Downslope Curvature Characteristics for Geology Landform Categories

	Downslope curvature			(percent/25meters) Standardized range		
Landform categories	Dominant & 2.class	%FQ[1]	Rank mag[2]	LL[3]	UL[4]	Rank var[5]
Lake	str* cv*	(77.80) (17.80)	(3)	-0.66	0.31*	(3)
Varied	cv* str*	(36.93) (25.69)	(19)	-2.77	1.75*	(19)
Terrace	cv* str*	(39.05) (26.26)	(16)	-2.46	1.67*	(17)
Flat	str* cv*	(39.05) (24.94)	(6)	-1.28	0.46*	(6)
Flat-Hummocky(0-3m)	str* cx*	(86.73) (7.58)	(2)	-0.38	0.49*	(2)
Flat-Rolling(0-3m)	str* cx*	(88.40) (7.09)	(1)	-0.37	0.45*	(1)
Rolling(1-3m)	str* cv*	(67.63) (17.34)	(5)	-0.89	0.75*	(4)
Rolling(3-10m)	str* cx*	(54.69) (23.88)	(8)	-1.26	1.44*	(13)
Rolling(>10m)	str* cx*	(35.77) (33.49)	(10)	-1.09	1.29*	(10)
Hummocky(1-3m)	cx* cv*	(34.13) (31.15)	(15)	-1.50	1.58*	(16)
Hummocky(3-10m)	cv* cx*	(39.54) (31.31)	(18)	-2.20	2.13*	(18)
Hummocky(>3m)	cv* str*	(38.28) (28.99)	(14)	-1.54	1.20*	(14)
Hum-Rolling(1-3m)	str* cv*	(70.23) (14.80)	(4)	-0.93	0.97*	(7)
Hum-Rolling(1-10m)	str* cx*	(57.28) (22.13)	(7)	-0.81	0.85*	(5)
Hum-Rolling(3-10m)	cx* str*	(38.28) (32.24)	(11)	-1.05	1.25*	(9)
Hum-Rolling(>3m)	cv* cx*	(35.89) (32.77)	(17)	-1.38	1.40*	(15)
Hum-Rolling(>10m)	cx* vcx*	(31.58) (26.64)	(20)	-5.90	6.95*	(20)
Hum-Ridged(>3m)	cv* str*	(38.85) (29.37)	(13)	-1.54	1.12*	(12)
Ridged(3-10m)	cv* cx*	(38.41) (30.00)	(12)	-1.01	1.05*	(8)
Ridge-Rolling(3-10m)	str* cv*	(53.20) (22.66)	(9)	-1.32	1.23*	(11)

[1] frequency, [2] magnitude, [3] lower limit, [4] upper limit, [5] variance, [6] coefficient of variance

* vcv = very concave (< -4.44%/25m), cv = concave (-4.44 to -0.44%/25m), str = straight (-0.44 to 0.44%/25m), cx = convex (0.44 to 4.44%/25m), vcx = very convex (> 4.44%/25m)

Table 6.6. Measures of Morphometric Distribution Similarities between Geology Landform Categories

Geology categories	1 Lake	2 Var	3 Terr	4 Flat	5 FlHu	6 FlRo	7 Roll	8 Roll	9 Roll	10 Hum	11 Hum	12 Hum	13 HuRo	14 HuRo	15 HuRo	16 HuRo	17 HuRo	18 HuRi	19 Ridg	20 RiRo
1 Lake	3																			
2 Varied		3																		
3 Terrace		1	3																	
4 Flat				3																
5 Flat-Hummocky	3				3															
6 Flat-Rolling	2				1	3														
7 Rolling(1-3m)				3			3													
8 Rolling(3-10m)			1	2			1	3												
9 Rolling(>10m)			1	2				3	3											
10 Hummocky(1-3m)			2					1	3	3										
11 Hummocky(3-10m)		1	3					1	1	2	3									
12 Hummocky(>3m)				2			2	3	2	1		3								
13 Hum-Rolling(1-3m)				2			3					2	3							
14 Hum-Rolling(1-10m)				2			3					1	3	3						
15 Hum-Rolling(3-10m)				1	2				3	3	2	1	2	1	3					
16 Hum-Rolling(>3m)					2			1	3	3	1		3	1	3	3				
17 Hum-Rolling(>10m)			1	1							1	1					3			
18 Hum-Ridged(>3m)				1			2	2	2	1		3	2	2	2	3		3		
19 Ridged(3-10m)				3			3	2	3			2	3	2	3	2		3	3	
20 Ridge-Rolling(3-10m)				2			2	3	2	1		3	2	2	2	3		3	3	3

A measure of 3 indicates that the two categories are similar for all morphometric distributions (local relief, slope gradient, and downslope curvature) at a 1% significance level using an F-test. For individual F-test results see Figure A2.4.1 to A2.4.3.

landform characteristic is related to the fact that category *flat* is associated with two landform features on the geology map, organic depressions and floodplains of the Beaver River. The form of these landform features are characterized by high frequencies of concave slopes (Table 6.5.3 and Figure A2.3.4). As a result, the variances of the morphometric distributions are larger.

Most *rolling*, *hummocky*, *hummocky-rolling*, and *ridged* landform categories associated with the same local relief modifier class are not significantly different according to the results of the F-test. The same landform categories often have similar dominant classes and standardized ranges also. For example, *rolling(3-10m)* resembles *hummocky(>3m)*, *hummocky-rolling(3-10m)*, *hummocky-rolling(>3m)*, and *ridged-rolling(3-10m)*. Some of these categories can be differentiated by inspecting the azimuth distributions. *Rolling(>10m)*, *hummocky-rolling(1-3m)*, *hummocky-rolling(1-10m)* and *ridged-rolling(3-10m)* show a bimodality for NE-SW, and E-W facing slopes (Figure A2.3.9, 13, 14, and 20), the same direction as *hummocky-ridged(9-15%)* of the soil classification. *Hummocky(>3m)* portrays a good example of the multimodality of hummocky landforms (Figure A2.3.12).

Hummocky(1-3m). *hummocky(3-10m)*, and *hummocky-rolling(>10m)* are associated with higher DTM relief values than indicated by the relief class modifier of the geology classification. The variable distributions are not representative for these three landform categories because the units are cut off at the margins of the data sets; the reduction in size of these landform units is expressed by the small areal extent of the units of less than 1 square kilometer (see percent of total area on Table 6.5.1). The high local relief values are generally associated with high slope gradient values except for *hummocky(1-3m)* which is represented by a dominant slope gradient class of low magnitude. An edge effect from neighbouring grid cells of higher elevation are most likely the reason for an disproportional increase of the local relief value for *hummocky(1-3m)*.

The same edge effect influences also the local relief distribution of the landform category *terrace*. *Terrace* is described as consisting of a flat tread and a steep riser (Howes and Kenk, 1988). This characteristic should be reflected in a bimodality of flat and steep slopes and low and high relief. Whereas local relief does not reflect this bimodality, the bimodality is slightly visible on the histograms for slope gradient (Figure A2.3.3). The large range of relief and slope gradient values are shown by high variances of the morphometric variable distributions which are similar to the variance for *hummocky(3-10m)* according to the F-test results. *Varied* is represented by an even higher variance than *terrace* caused by a high variability of the land surface along the river and creek valley walls which are partly related to landslides as described in Chapter 4.

In summary, geology landform categories are more difficult to differentiate than soil landform categories because many categories are defined by two surface expression labels. For example, *flat-rolling*, *hummocky-rolling* and *ridged-rolling* all consist of a combination of *rolling* with another surface expression label. Furthermore, the local relief modifiers of the geology classification extend more often over two class intervals than do the slope gradient modifiers of the soil classification. Lower values of percent dominant class overlap, relative variance, discriminatory power, and a higher count of morphometric distribution similarities according to the F-test results for geology landform categories compared to the equivalent values for soil landform categories indicates a lack of precision in defining geology landform categories.

6.5 Comparison of the Sand River Geology Landform Classification with the County of St.Paul Soil Landform Classification

6.5.1 Representation of Statistical Measures

The comparison of the geology and soil landform classification is presented in the form of cross-tabulations and as a measure of morphometric distribution similarities. From the cross-tabulations, the correspondence between the soil and geology classification was calculated according to the total overlap of landform categories of the one classification with the corresponding dominant category of the other classification. The measure of similarity was derived by counting the number of times morphometric distributions were not significantly different between two landform categories at a 1% significance level using an F-test (Table A2.3.1 to A2.3.3). To facilitate the association between the two statistical measures, percent category overlap and number of morphometric distribution similarities were combined into one table of landform category correspondences. The correspondences between both classifications differ because the number of categories varies between both classifications. For this reason, two tables were generated; Table 6.7 presents the comparison of the geology categories with the soil categories and Table 6.8 shows the comparison of the soil categories with the geology categories.

6.5.2 Results

Comparing the geology and the soil landform data sets, 54.19% of the geology landform categories overlap with a corresponding dominant soil landform category (Table 6.7) and 49.02% of the soil landform categories overlap with a corresponding dominant geology landform category (Table 6.8). These values suggest a low correspondence between the landform categories of the two classification schemes which can be attributed to two facts: first, the number of categories differ between the two landform classifications (the soil survey map contains 15 categories and the geology map contains 20 categories); and, second, the delineation of the landform units was based on two different quantitative modifiers (slope gradient was used in the soil survey and local relief in the geology survey).

Inspecting the tables of correspondence (Table 6.7 and 6.8), landform categories of one classification correspond frequently with many categories of the other landform classification not only according to the measures of percent overlap but also according to the measure of similarities for all morphometric distributions. In many instances, the correspondence according to percent overlap does not coincide with the correspondence according to measure of morphometric distribution similarities. This apparent diversity of correspondence between the different landform categories requires a more detailed discussion to provide a better understanding of the relationships between the landform categories of the soil and geology landform classifications.

Most landform categories of the one classification correspond with landform categories of the other classification which have similar slope gradient or local relief magnitudes. For example, category *lake* of the geology classification overlaps highly with category *lake* of the soil classification, *flat* of the geology classification corresponds with *level(0-2%)* of the soil classification, *flat-hummocky*, *flat-rolling*, *rolling(1-3m)*, and *hummocky-rolling(1-3m)* with *undulating*, etc. In most instances, the overlap resulting from the comparison of soil with geology categories correspond with the overlap resulting from the comparison of geology with soil categories. Shifts in overlap, however do occur, especially for categories consisting of large areal units. For example, soil landform category *undulating(2-5%)* does not correspond highly with the geology landform categories *flat-rolling* or *flat-hummocky*, although these two categories showed the highest overlap with *undulating(2-5%)* for the geology with soil classification comparison. In contrast,

Table 6.7. Correspondence between Geology and Soil Categories According to Percent Category Overlap and Measures of Morphometric Distribution Similarities

Geology categories	**Soil Categories** Lake	Level 0-2	Level 0-10	Undul[1] 0-5	Undul[1] 2-5	Diss[2] >5	Diss[2] >10	Hu-In[3] 9-30	Hu-In[3] >15	Hu-Ri[4] 5-9	Hu-Ri[4] 9-15	Hum[5] 5-9	Hum[5] 9-15	Hum[5] >15	Hum[5] 5-15%
Lake	**88.98** (3)	2.45 (2)		(2)	0.34 (1)					3.38 (1)		0.24	2.35	2.25	(3)
Varied		5.24	**20.44** (1)	0.29	17.78	2.42 (1)	**29.96** (1)					11.16	9.17	3.55 (1)	
Terraced			34.80 (3)			(1)	**64.91** (3)						0.29	(3)	
Flat	1.08	**53.08**	9.92 (2)	4.30	11.78 (1)	(1)	3.69	0.08 (2)	(2)	1.13 (1)	1.58 (1)	7.52 (1)	5.11 (2)	0.63 (2)	0.10
Flat-Hummocky	(3)	13.61 (2)	0.13	(1)	**84.02** (2)					(2)		(1)	2.25		(2)
Flat-Rolling	(1)	4.55	0.59	(1)	**94.87**										(1)
Rolling(1-3m)		26.56	1.26 (1)		**42.47** (1)	(1)	14.02	(2)	(1)	5.73	(3)	9.51 (3)	0.42 (2)	(1)	
Rolling(3-10m)		6.40	1.83 (2)		**54.67**	0.16 (1)	4.02	(3)	(3)	0.18		25.36	3.37 (3)	3.99 (3)	
Rolling(>10m)	0.20	6.57	(2)		2.19	0.36 (1)	3.90 (1)	1.71 (3)	(3)	1.24		6.63	**76.92** (2)	0.28 (2)	
Hummocky(1-3m)			(1)				(3)	(1)	(2)				(1)	(2)	
Hummocky(3-10m)			(3)			(1)	(3)	28.76		5.84			**65.39**	(2)	
Hummocky(>3m)	1.35	4.19	(2)		0.02	(1)		1.84 (3)	0.72	8.44 (1)	(1)	(3)	**50.11** (3)	33.34	
Hum-Rolling(1-3m)	0.79	2.88	0.25		**83.65** (1)					(2)	(3)	5.05 (3)	7.39 (2)		
Hum-Rolling(1-10m)		5.94	0.93	0.37	19.52 (3)		0.01		0.52	5.03 (3)	4.16 (3)	**50.12** (3)	12.17 (1)	0.49	0.75
Hum-Rolling(3-10m)		0.59	(2)		0.08	(1)	2.37 (1)	(3)	(3)			**46.46**	**50.15** (2)	(2)	
Hum-Rolling(>3m)			(2)			(1)		(3)	(3)				(3)	(3)	
Hum-Rolling(>10m)							(1)								
Hum-Ridged(>3m)	0.26	2.37						(2)	11.77 (2)	0.03	(2)	(2)	**60.42** (3)	25.15	
Ridged(3-10m)			(2)			(1)		(2)	(2)			(1)	(3)	(2)	
Ridge-Rolling(3-10m)	0.03	8.76	(2)		3.24	(1)		(3)	**47.19** (3)	0.97	7.96 (1)	19.03	12.83 (3)	(2)	

(Number of morphometric distribution similarities are listed in brackets. A measure of 3 indicates that the two categories are similar for all morphometric distributions (local relief, slope gradient and downslope curvature) at a 1 % significance level using an F-test. For individual F-test results see Figure A2.5.1 to A2.5.3)

[1] Undulating, [2] Dissected, [3] Hummocky-Inclined, [4] Hummocky-Ridged, [5] Hummocky

54.19% total overlap of geology landform categories with dominant soil landform categories

Table 6.8. Correspondence between Soil and Geology Categories According to Percent Category Overlap and Measures of Morphometric Distribution Similarities

Soil categories	Geology categories																			
	Lake	Var[1]	Terr[2]	Flat	Fl-Hu[3] 0-3	Fl-Ro[4] 0-3	Roll[5] 1-3	Roll[5] 3-10	Roll[5] >10	Hum[6] 1-3	Hum[6] 3-10	Hum[6] >3	Hu-Ro[7] 1-3	Hu-Ro[7] 1-10	Hu-Ro[7] 3-10	Hu-Ro[7] >3m	Hu-Ro[7] >10	Hu-Rl[8] >3	Ridge 3-10	Rl-Ro[9] 3-10 m
Lake	84.37			3.95					0.16			9.27	1.70					0.42		0.14
	(3)				(3)	(1)														
Level(0-2%)	0.50	2.11		41.87	4.69	0.15	10.40	6.29	1.17			5.19	1.33	15.79	0.07			0.81		8.62
	(2)																			
Level(0-10%)		38.1	2.75	36.24	0.21	0.09	2.29	8.33					0.53	11.41						
		(1)	(3)	(2)			(1)	(2)	(2)	(1)	(3)	(2)			(2)	(2)			(2)	(2)
Undulating(0-5%)		2.56		75.61										21.83						
	(2)				(1)	(1)														
Undulating(2-5%)	0.03	3.36		4.36	13.59	1.52	7.80	25.22	0.18			0.02	18.12	24.31						1.50
	(1)			(1)	(2)	(2)	(1)						(1)	(3)						
Dissected(>5%)		80.58						14.05	5.37											
		(1)	(1)	(1)			(1)	(1)	(1)		(1)	(1)			(1)	(1)			(1)	(1)
Dissected(>10%)		45.37	4.17	10.95			20.67	14.88	2.61					0.13	1.22					
		(1)	(3)						(1)	(3)	(3)				(1)		(1)			
Hum-Inclined(>9%)				1.61					8.19		17.18	73.02								
				(2)			(2)	(3)	(3)	(1)	(3)			(3)	(3)		(2)	(2)	(3)	
Hum-Inclined(>15%)												16.44		21.22				62.35		
				(2)			(1)	(3)	(3)	(2)		(3)			(3)	(3)		(2)	(2)	(3)
Hum-Ridged(5-9%)	0.90			1.16			2.93	0.23	0.29		0.17	16.29		17.42				0.01		60.60
	(1)			(1)	(2)								(2)	(3)						
Hum-Ridged(9-15%)				9.39										83.44						7.17
				(1)			(3)					(1)	(3)	(3)				(2)		(1)
Hummocky(5-9%)	0.03	2.38		3.14			1.97	13.18	0.62				1.23	70.38	2.93					4.14
				(1)	(1)		(3)					(1)	(3)	(3)				(2)	(1)	
Hummocky(9-15%)	0.26	2.02		2.20	0.42		0.09	1.81	7.49		0.80	40.54	1.87	17.67	3.27			11.33		10.24
			(1)	(2)			(2)	(3)	(2)	(1)		(3)	(2)	(1)	(2)	(3)		(3)	(3)	(3)
Hummocky(>15%)	0.59	1.83		0.63				5.02	0.06			63.05		1.65				11.03		16.13
		(1)	(3)	(2)			(1)	(3)	(2)	(2)	(2)	(3)			(2)	(3)			(2)	(2)
Hummocky(5-15%)				3.86										96.14						
	(3)				(2)	(1)														

(Number of morphometric distribution similarities are listed in brackets. A measure of 3 indicates that the two categories are similar for all the morphometric distributions (local relief, slope gradient, and downslope curvature) at a 1% significance level using an F-test. For individual F-test results see Figure A2.5.1 to A2.5.3)

[1] Varied, [2] Terrace, [3] Flat-Hummocky, [4] Flat-Rolling, [5] Rolling, [6] Hummocky, [7] Hummocky-Rolling, [8] Hummocky-Ridged, [9] Ridged-Rolling

49.02 percent total overlap of soil categories with dominant geology categories

undulating(2-5%) shows a dominant overlap with *hummocky-rolling(1-10m)* although *hummocky-rolling(1-10m)* overlaps mainly with *hummocky(5-9%)* of the soil classification. Both categories, *hummocky-rolling(1-10m)* and *undulating(2-5%)* cover large areas of the landform maps and consequently often appear as the dominant corresponding class.

The measure of morphometric distribution similarities can be used as another indicator to detect or confirm the correspondence between two categories. In most instances, a dominant overlap between categories is associated with similarities for all morphometric distributions between the same categories. In other instances, the lack of morphometric distribution similarities may be an indicator for a misinterpretation or mislabelling of the categories by the photointerpreter. For example, *rolling(3-10m)* shows a dominant overlap with *undulating* but according to the number of morphometric distribution similarities no correspondence exists between these two categories because *undulating* is associated with landforms of lower magnitude and variance than *rolling(3-10m)*.

The measure of morphometric distribution similarities can also be used as an indicator to point to those categories which do not overlap with the category but have similar morphometric distributions. This measure applies, for example, to those geology categories which are located outside of the boundary of the County of St. Paul and do not overlap with any soil category. *Hummocky-rolling(>3m)* is such a category which corresponds with soil categories *hummocky-inclined(>9%)*, *hummocky-inclined(>15%)*, *hummocky(9-15%)*, and *hummocky(>15%)*. Other categories, which show a dominant overlap with one category, may be similar to another category also. For example, *hummocky(9-15%)* of the soil classification is not significantly different from *hummocky(>3m)*, *hummock-rolling(>3m)*, *hummocky-ridged(>3m)*, *ridged(3-10m)*, and *ridged-rolling(3-10m)*. However, the measure of morphometric distribution similarity has to be used with caution. For example, *hummocky(5-15%)* is not significantly different from category *lake* of the geology classification. But the standardized range and the coefficient of variance differs between the categories because the mean of the *lake* category is lower than the variance as has been described in section 6.4.2.

The relationship between the categories *varied*, *flat*, and *terrace* of the geology classification and *level(0-2%)*, *level(0-10%)*, and the two *dissected* categories of the soil classification is complex. The complexity, however, is not related to differing landform delineations from airphotos but to differing surface expression definitions.

Varied in the geology classification describes two landform features, river valley walls and creek valleys. River valley walls are represented as *dissected(>10%)* and *dissected(>5%)* on the soil classification, whereas the creek valleys are labelled as *level(0-10%)* on the soil classification. Consequently, *varied* overlaps with all three categories which is also reflected by a bimodality of the classed slope gradient distribution of 9 to 15 percent slope and 2 to 5 percent slope (Figure A2.3.2 and Table 6.5.2). The high variance of the slope gradient distribution for *varied* is a result of this bimodality which is far higher than the variance for *dissected* or *level(0-10%)* of the soil classification. Consequently, the morphometric distributions do not correspond between *varied* and *level(0-10%)*, and *varied* and *dissected(>10%)* except for downslope curvature (Figure A2.5.3).

Additionally, *level(0-10%)* represents not only creek valleys mapped as *varied* on the geology map, but also floodplains mapped as *flat* on the geology map. For this reason, no strong resemblance of *level(0-10%)* in respect of variances or standardized ranges is indicated with the one or the other geology class. Instead, the morphometric distributions of the soil category *level(0-10%)* are not significantly different from many morphometric distributions representing other geology landform categories.

Furthermore, geology landform category *terrace* is not significantly different from the soil categories *level(0-10%)* and *dissected(>10%)* according to the morphometric distribution similarities. In this case the similarity is also reflected by an overlap between the categories. But according to the dominant class, standardized range and coefficient of variance of local relief and slope gradient (Table 6.3.1 and 6.3.2, and 6.5.1 and 6.5.2), there exists no resemblance between these categories. And finally, category *flat* of the geology classification not only represents floodplains but also represents poorly drained depressions mapped as *level(0-2%)* on the soil classification as indicated by a high overlap between the two categories. However, the variances differ between the two categories which is a result of category *flat* being associated with two landform features.

As described in detail above, the relationship between the landform categories of the soil and geology landform classifications is not as straight forward as expected given the correspondence of surface expression definitions (Table A1.3). The complexity of the correspondence can be attributed to two reasons: first, double labelling of surface expression names and close resemblance of the quantitative modifier classes especially of the geology landform classification are the reason for the high correspondence between so many similar landform categories; and second, the usefulness of the F-test for determining morphometric variable distribution similarities is limited because only the variances not the means of the distributions are compared. The general application of the F-test in landform analysis is further discussed in the next section.

6.6 Discussion and Summary

6.6.1 An Assessment of the Application of F-Tests in Landform Analysis

The application of the F-test to compare morphometric variable distributions is not always appropriate for determining similar landform categories and requires further discussion. The results of the F-test indicate more often a similarity between two morphometric variable distributions for which the similarity according to the standardized range does not exist. This inconsistency is due to an assumption made for the F-test that two distributions having similar variances also have similar means. This assumption implies that for an increase of the standard deviation the mean increases also as expressed in a linear relationships. Slope gradient, however, does not show this linear relationship as was stated by Evans (1972). Evans demonstrated that the standard deviation increases disproportionally for a low mean expressed by a curvilinear relationship and a positive skewness of slope gradient distributions (O'Neill and Mark, 1987). For this reason, landform categories represented by a low mean of local relief and slope gradient such as *lake*, *level*, *flat*, and *undulating* are all represented by a coefficient of variance higher than 1.0, whereas areas of a high mean of slope gradient and of a high mean of local relief, such as *dissected* or *varied*, have coefficients of variance less than 1.0. If the variances of two landform categories with a high and low coefficient of variance are compared using an F-test, the result of the F-test may suggest similarities in distributions, whereas the means of the two categories differ. Consequently, the F-test can only be used as a screening process for identifying two distributions which show no significant difference. If the coefficient of variance differs between these two categories, it can be concluded that neither the two means nor the standardized ranges correspond between the two categories. To test if the difference between the means of these categories is significant, a t-test can be applied in future analysis.

Pike and Thelin (1989) also reported anomalous values for coefficients of variance which were used to compare the level of homogeneity for different American physiographic regions. Pike and Thelin stated that physiographic provinces such as the Superior Upland and St.Lawrence Valley show a higher heterogeneity than expected. Pike and Thelin associated these anomalies with an incorrectness of the Fenneman taxonomy of physiographic regions, whereas the real reason could be related to the positive skewness of slope gradient data.

6.6.2 Summary

The quantitative analysis presented in this chapter reveals a lower correspondence between the soil and geology landform classification than expected particularly after comparing the qualitative descriptions of the two landform classifications. These differences are partly related to double labelling of surface expression which dilutes the exact definition of landform categories. A similar lack of precision is caused by extending the quantitative modifier class, which is used to differentiate between two categories of the same surface expression, over two class intervals. Additionally, the two classifications are based on two different quantitative modifiers; local relief is used in the geology classification and slope gradient in the soil classification. However, not only is the correspondence between the two classifications insufficient neither is the correspondence between the quantitative modifiers of the classifications and the corresponding DTM distributions.

All these inaccuracies can be related to the following error sources:

1. The boundaries of the soil and geology unit polygons may not coincide with the boundaries of the landform units themselves because other parameters have priority for the delineation of the boundaries (e.g. material modifiers) (Niemann, 1987; Horvarth *et al.*, 1987; Crown, personal correspondence).
2. Boundary lines of several parameters are never identical although they may show similarities. Consequently, the unit boundary on the maps form a compromise between several parameter boundaries (Smith and Campbell, 1989; Burrough, 1986; Thie *et al.*, 1979).
3. Especially in geomorphology, landform changes are gradual and never abrupt which may result in variations of boundary locations from survey to survey (Burrough, 1986; Smith and Campbell, 1989).

4. Errors are introduced during digitizing, encoding, and vector to raster conversion of the soil and geology landform data sets (Walsh *et al.*, 1987; Burrough, 1986; Smith and Campbell, 1989). Some landform categories were not encoded as precisely as represented in the legend of the geology landform classification due to limitations in the numerical representation. For example, *hummocky(1-3m)* over *rolling(3-10m)* was encoded as *hummocky-rolling(1-10m)*.
5. Slope gradient was probably overestimated on the soil survey map caused by inaccurate slope measurements from aerial photographs (Johnson, 1988) due to a strong vertical exaggeration by stereoscopic viewing. An underestimation of the DTMs caused by faulty DEMs, smoothing of the DEMs, or surfacing of the DEMs is less likely.
6. The DEM, geology and soil landform data sets vary according to their grid resolution as a result of using different map scales. The DEMs were surfaced at a scale of 1:20,000, whereas the landform units were digitized from 1:50,000 maps. The difference in scale is manifested by a grid resolution of 25x25 meters for the DEM and 50x50 meters for the soil and geology landform data sets. Consequently, the overall accuracy can only be as good as the least accurate parameter (Walsh *et al.*, 1987).

Despite the analysis being influenced by the preceding list of error sources, the following trends are apparent which confirm the interpretations made in Chapters 4 and 5. Landform categories described in the geology classification as *hummocky* over *rolling* are difficult to grasp numerically; but ranking of landform categories contribute to an understanding of the relief and slope gradient magnitude and landform variability. The quantitative modifiers of the landform classifications should be more precisely specified than currently described in the soil and geology survey map legends. Generally, slope gradient values are overestimated on the soil survey map and local relief underestimated on the geology map. The landform classification should not be based solely on the dominant morphometric variable classes but some form of variance measure should be added to represent the variability of landforms. The standardized range was introduced in this study to represent the majority of the morphometric variable distribution and was found to provide a more accurate measure than the mode.

The selected morphometric variables were appropriate for characterizing the different topographic properties of the landforms. However, based on the F-test results, the following two observations were made: first, the F-test results do not correspond in all instances with similarities of landform categories according to the mode and mean; differences between the mean and variance of two landform categories were however expressed by different coefficients of variance. Second, landform categories may not be significantly different according to the distribution of one morphometric variable but are different according to distributions of other variables; only the combination of F-test results derived for all variables provides an account for landform similarities and differences. For the comparison of the different landform categories, as implemented in this chapter, the statistical analysis had to be applied separately to the morphometric variables to describe the morphometric characteristic individually. The results of the F-test analysis, however, suggests that the individual variables have to be integrated into a multivariate analysis for the classification of landform categories from DTMs; this will be addressed in the following chapter.

7. Automated Landform Classification

In this research, landform categories have so far been delineated using digital terrain models (DTMs) and visual image interpretation as described in Chapter 4. The image interpretation process, however, is subjective relying on the operator's expertise, knowledge of the area, and ability to differentiate between tone and texture patterns on an image. In this chapter, an automated classification methodology is described which replaces the descriptive image interpretation process by a quantitative decision making process. The automated classification is assumed to be more reliable than the sometimes vague image interpretation because the decision making process remains no longer the task of the photo interpreter but is assigned to the computer (Schowengerdt, 1983).

Automated classification requires an integrated, multivariate and synthetic systems approach (Dobson, 1983; Pike, 1988) which cannot be achieved by simply overlaying the individual DTMs to generate a single new model of morphometric class composites (Burrough, 1986; Schmid, 1987; Gardiner, 1976). Such a summation of morphometric characteristics resembles an inventory rather than a classification and lacks the synthesis required in a landform classification (Wright, 1972). Additionally, a multitude of meaningless polygons is created because each variable consists of different units of varying areal extent (Thie *et al.*, 1979). To synthesize the morphometric characteristics to a limited number but meaningful landform categories, a multivariate statistical approach has to be applied (Burrough, 1986; Pike, 1988). In such a statistical approach, the interrelationship between the morphometric characteristics of landform categories, represented by DTMs of local relief, slope gradient and downslope curvature, are interpreted and a set of quantitative decision rules is generated providing the basis for the classification.

The two objectives of the automated landform classification were: first, to replicate as accurately as possible an existing specific landform classification based on landform categories derived using conventional airphoto interpretation; and second, to reproduce a landform classification which should be sufficiently generalized to be applicable to any Canada land survey. The two automated landform classifications implemented in this thesis were based on supervised training field selections; for the first classification, training fields were selected from the County of St.Paul soil landform map. For the second classification, training fields were selected from DTM maps, as described in Chapter 4.

7.1 Principles of the Automated Landform Classification

The assumption that landform categories can be discriminated on the basis of a set of measurements defined as geometric signatures (Pike, 1988) provides the basis for the application of image processing and classification techniques in landform analysis (Weibel and DeLotto, 1988). As described in Chapter 2, the use of conventional automated classification techniques considers only attribute characteristics determined for single grid points. This technique may be sufficient to classify discrete landform elements but not sufficient to classify landform patterns. For example, a single grid point represented by morphometric class values of low local relief, gentle slope gradient and slight concavity can be part of a lower footslope of a hummock, ridge, tread of a terrace, or valley. This study is not concerned about the classification of a specific landform element, such as a footslope, but focuses on the classification of landform patterns, such as *ridged* or *hummocky* landforms, described in general geomorphometry by a continuous, rough surface (Evans, 1981).

For the classification of landform patterns, spatial characteristics in the form of texture and context information have to be incorporated into the classification process. Pike (1988) and Weibel (1989) used statistical texture measures to discriminate and classify different landform types. But the textural classifiers were still used as point classifiers and not as contextual classifiers although the information for determining the texture measure was derived from the neighbourhood surrounding the grid point. Weibel (1989) was aware of this deficiency and improved the classification by including a post-processing region growing algorithm based on a method introduced by Starr and Mackworth (1978). In this algorithm, elements ambiguously classified according to a maximum likelihood classifier were assigned to a surrounding region consisting of unambiguously classified elements. Other region growing algorithms which use spatial-based contextual classifiers have been described by Kettig and Landgrebe (1976), Landgrebe (1980), Pavlidis (1982), and Cross *et al.* (1988).

In addition to a statistical approach to texture and context analysis, a structural approach to pattern recognition has been described by Fu (1982).

Chorowicz *et al.* (1989) used such a structural approach to classify landform types by applying a descriptive language modifier; geomorphological pattern characteristics defining the landform type in the form of a grammatical sentence were recognized from a succession of landform elements along profile lines. Dikau (1990a), in turn, proposed a landform classification model in which point descriptors based on statistical texture measures, and contextual descriptors based on structural modifiers, would be used simultaneously. According to Dikau (1989; 1990a), hierarchically ordered landform components should be synthesized to larger landform components based on semantical modelling rules. The landform components are aggregated according to a specific catalogue of spatially defined descriptors.

The use of a structural approach to determine landform pattern in comparison to a statistical approach is more difficult to model (Harris, 1980) and has not been fully automated in landform classification either by Chorowicz *et al.* (1989) or by Dikau (1989; 1990a). In contrast, a relatively simple context classifier based on frequencies is described by Wharton (1982) which can be easily implemented into an automated classification using multivariate statistics (Gong and Howarth, 1992; Eyton, 1993). This approach utilized the contextual information derived from neighbourhoods in the form of land cover class frequency counts to provide the data base for a cluster analysis. A similar frequency-based contextual classifier was used in this research to classify landform patterns which replaces the textual point classifier used by Pike (1988) and Weibel (1989).

7.2 Frequency Signatures

Two prerequisites have to be fulfilled before the above described contextual classifier can be applied in landform classification; first, data sets containing a limited number of variables representing landform characteristics have to be available in order not to exceed the total number of variables manageable in a multivariate analysis; and, second, a neighbourhood size representing homogeneous landform patterns has to be selected for which the contextual classifier can be determined. Referring to the first point, Eyton (1993) used a mix of different land cover types as land use characteristics. Initially, land cover types were classified from the spectral bands of the remotely sensed data. The frequencies of these land cover types obtained for convolved neighbourhoods formed the data base for the preceding land use classification. In contrast, Gong and Howarth (1992) reduced the grey level vectors of the spectral bands through compression using principal component analysis. In this research, frequency counts were determined for DTM classes of local relief, slope gradient and downslope curvature as classed in previous chapters (Table A2.4 and A2.5). The use of morphometric classes for determining the frequency counts is suitable for this research because the Canadian System of Soil Classification (E.C.S.S., 1987a), the Terrain Classification System (Howes and Kenk, 1988), the County of St.Paul soil landform classification (Brierley *et al.*, 1990), and the Sand River surficial geology landform classification (Andriashek and Fenton, 1989) use classed morphometric modifiers to discriminate between landform categories. Azimuth classes representing different modality status were not used as variables for the frequency counts because of the difficulty involved in the automated determination of the modality status as described in Chapter 6.

As for the second prerequisite, the contextual classifier has to be determined from neighbourhoods of homogeneous texture as described in Chapter 5. In this classification, the selection of a fixed neighbourhood size was based on the results of the texture analysis applied to the slope gradient distribution. The slope gradient distribution was used because it forms the single most important morphometric variable in landform analysis. The selected neighbourhood size of 11x11 grid points or 275x275 meter for slope gradient is close to the neighbourhood size of 13x13 or 325x325 meter used by Weibel (1989) and the area defined by a 300 meter radius proposed by Speight (1974).

Only a certain range of landforms, however, can be identified by a fixed neighbourhood size (Weibel and DeLotto, 1989) because landforms vary in scale. To consider the varying scale and therefore context of a landform, Weibel and DeLotto suggested the use of variable neighbourhood sizes derived from a hierarchical classifier. This approach has been employed in image processing by Tanimoto and Pavlidis (1975), Catanzariti and Mackworth (1978), Cross *et al.* (1988), and Franklin and Wilson (1991; 1992). The classification implemented in this chapter, however, is based on a fixed neighbourhood size for the following two reasons: first, computer algorithms are easier to implement using fixed neighbourhood sizes than the more complex algorithms required to determine varying neighbourhood sizes; and, second, fixed neighbourhood sizes provide equal distances which guarantee an equal information spread (Weibel, 1989). Equal information spread is of importance to this landform classification because, according to the Canadian Ecological Land Classification (Wiken, 1980), landform units mapped at a certain scale are supposed to represent landforms or landform patterns of a certain size and extent only. The landform map scale of 1:250,000 to 1:50,000 associated with the County of St.Paul soil landform map and the Sand River geology landform map refers to the ecosection level which represents assemblages of local landforms or a local landform (Table 2.1). The assumption was made for this research that the individual landform patterns mapped at the ecosection level can be represented by the fixed neighbourhood size of 275x275 meters.

7.3 Classification Methodology

The classification of landform categories is based on supervised training field selection. Supervised training field selection was chosen over unsupervised selection because the determination of training fields is based on specific landform categories defined by the Canadian System of Soil Classification (E.C.S.S., 1987a), the County of St.Paul soil classification (Brierley *et al.*, 1990), the Terrain Classification System (Howes and Kenk, 1988), and the Sand River geology classification (Andriashek and Fenton, 1989). Decision rules for classifying the entire study area were generated from the morphometric characteristics of the selected training field samples using discriminant analysis. The frequency counts of four local relief, five slope gradient and five downslope curvature categories, as classed in previous chapters (Table A2.4 and A2.5), formed the data base for the discriminant analysis implemented by the SPSSX statistical package (SPSS Inc., 1986). Constants and coefficients derived according to Fisher's (1936) linear classification functions, which define the feature space of the landform categories, were used to classify the entire data set. Experiments working with DTMs showed that the DTMs are nearly normal. One category of each of the three variable groups failed the tolerance test implemented by the SPSSX discriminant analysis because the fixed neighbourhood size is a closed system and will always produce a constant sum of frequency counts. As a result, the variance of one category per variable group can be accounted for by the other categories. Consequently, one category per variable group was removed from the classification. Finally, the resulting landform classification was smoothed to reduce noise and edge effects using a majority filter for a convolved 5x5 neighbourhood.

Training sample sets were collected for two different landform classifications: first, training areas were sampled on the basis of landform categories delineated on the County of St.Paul soil survey map; and, second, training areas were selected from DTM maps according to a synthesis of landform definitions described by Brierley *et al.*, (1990), E.C.S.S. (1987a), Andriashek and Fenton (1989), and Howes and Kenk (1988) (Table A2.1 to A2.4). The landform training samples were selected from a hillshaded-slope-gradient-overlay and a hillshaded-local-relief-overlay (overlays are not shown here). No training area samples were derived solely on the basis of the Sand River surficial geology landform classification (Andriashek and Fenton, 1989) because the quantitative analysis (Chapter 6) showed that the geology landform categories were not distinguishable as well as the County of St.Paul soil landform categories. Double naming of geology landform categories and overlap of local relief class ranges would have resulted in a poor discrimination.

7.4 Automated Soil Landform Classification

7.4.1 Classification Process

Samples representing the County of St.Paul soil landform categories were collected in a supervised training field selection except of landform category *dissected(>5%)* which has a too small areal extent to represent a training area of sufficient size. The overall correct classification (57.57%) of the training field samples based on the first discriminant analysis was very low (Table 7.1). This low value is explained by the morphometric attribute similarities of several categories as described in Chapter 6. In a second discriminant analysis, category *lake* was merged with category *level(0-2%)*, categories *undulating(0-5%)* and *hummocky(5-15%)* were merged with category *undulating(2-5%)*, and categories *hummocky-inclined(9-30%)* and *hummocky-inclined(15-30%)* were merged with category *hummocky(>15%)*. The decision to merge categories was based on the results of the contingency table of the first discriminant analysis (Table 7.1) and the landform category correspondences represented by similarity measures of morphometric distributions described in Chapter 6 (Table 6.4). Furthermore, the remaining landform category samples were cleaned by removing observations which were misclassified in the previous discriminant analysis. The overall correct classification improved from 57.67% to 94.26% in the final discriminant analysis (Table 7.2). The remaining nine

Table 7.1. Classification Results of Automatically Generated Soil Landform Categories Based on Supervised Training Field Selection According to County of St. Paul Soil Landform Categories: First Discriminant Analysis

Actual category membership (No. of observations)	**Predicted category membership**													
	1 Lake	2 Level	3 Level	4 Und	5 Und	7 Diss	8 Huin	9 Huin	10 HuRI	11 HuRI	12 Hum	13 Hum	14 Hum	15 Hum
1 Lake (350)	**289** **82.6**	61 17.4												%
2 Level(0-2%) (810)	461 56.9	**114** **14.1**		189 23.3										46 5.7%
3 Level(0-10%) (220)			**135** **61.4**				29 13.2	8 3.6	45 20.5	3 1.4				%
4 Undulating(0-5%) (195)		18 9.2		**116** **59.5**	22 11.3									39 20.0%
5 Undulating(2-5%) (746)		87 11.7		61 8.2	**359** **48.1**				35 4.7		113 15.1			91 12.2%
7 Dissected(>10%) (758)						**567** **74.1**	12 1.6		7 0.9	39 5.1	1 0.1	134 17.7	3 0.4	%
8 Hum-Inclined(>9%) (210)			16 7.6				**152** **72.4**	6 2.9					36 17.1	%
9 Hum-Inclined(>15%) (238)			7 2.9			5 2.1	21 8.8	**116** **48.7**	34 14.3		11 4.6	40 16.8	4 1.7	%
10 Hum-Ridged(5-9%) (644)					57 8.9				**433** **67.2**		84 13.0			70 10.9%
11 Hum-Ridged(9-15%) (220)							5 2.3			**214** **97.3**			1 0.5	%
12 Hummocky(5-9%) (867)					69 8.0				126 14.5		**601** **69.3**	60 6.9		11 1.3%
13 Hummocky(9-15%) (711)			31 4.4			48 6.8	52 7.3	31 4.4	63 8.9	15 2.1	74 10.4	**391** **55.0**	6 0.8	%
14 Hummocky(>15%) (612)			103 16.8			26 4.2	59 9.6	9 1.5		6 1.0		88 14.4	**321** **52.5**	%
15 Hummocky(5-15%) (110)				44 40.0	7 6.4				3 2.7					**56** **50.9%**

Overall correct classification 57.67%

Table 7.2. Classification Results of Automatically Generated Soil Landform Categories Based on Supervised Training Field Selection According to County of St.Paul Soil Landform Categories: Final Discriminant Analysis

Actual category	**Predicted category membership**								
membership (No. of observations)	2 Level	3 Level	5 Undul	7 Diss	10 HuRi	11 HuRi	12 Hum	13 Hum	14 Hum
2 Level(0-2%)	**888**		24						
(912)	**97.4**		2.6						%
3 Level(0-10%)		**134**			8				
(142)		**94.4**			5.6				%
5 Undulating(2-5%)	4		**756**		13		1		
(774)	0.5		**97.7**		1.7		0.1		%
7 Dissected(>10%)				**543**		12		6	1
(562)				**96.6**		2.1		1.1	0.2%
10 Hum-Ridged(5-9%)			32		**434**				
(466)			6.9		**93.1**				%
11 Hum-Ridged(9-15%)		3				**214**			
(217)		1.4				**98.6**			%
12 Hummocky(5-9%)			1		42		**566**	7	
(616)			0.2		6.8		**91.9**	1.1	%
13 Hummocky(9-15%)		2		1	24		2	**354**	13
(396)		0.5		0.3	6.1		0.5	**89.4**	3.3%
14 Hummocky(>15%)		49		9				11	**463**
(532)		9.2		1.7				2.1	**87.0%**

Overall correct classification 94.26%

categories are listed in the legend of Figure 7.1 which shows the result of the automated soil landform classification.

7.4.2 Comparison of the Automated Soil Landform Classification with the County of St.Paul Soil Landform Classification

A visual comparison between the automated soil landform classification map (Figure 7.1) and the County of St.Paul soil landform map (Figure 3.5) shows that the overall landform pattern corresponds between the two maps. Especially areas of low relief classified as *level(0-2%)* and *undulating(2-5%)*, and the Beaver River valley walls classified as *dissected(>10%)* are represented by the same categories on both maps. In contrast, *hummocky* and *ridged* landform units are not represented by only one category in the automated soil landform classification. For example, landform categories *hummocky(5-9%)*, *hummocky-ridged(5-9%)* and *hummocky-ridged(9-15%)*, located in the center of the County of St.Paul landform map, consist of a composition of *hummocky-ridged(5-9%)*, *hummocky(5-9%)*, and *undulating(2-5%)* categories on the automated soil landform classification map. The representation of a single County of St.Paul soil landform category by a composition of automatically classified soil landform categories is reflected by a low overall class correspondence of only 32.60% (Table 7.3). The number of category overlaps shown in Table 7.3 are similar with the landform category correspondences represented by similarity measures of morphometric distributions described in Chapter 6 (Table 6.4).

The automatically classified landform categories, which overlap with a single County of St.Paul soil landform category, such as *hummocky* and *hummocky-ridged* (Table 7.3), are often arranged in a certain pattern on the automated soil landform classification map. For example, areas of very high convexity and concavity, such as the edges of knobs or kettles within the County of St.Paul soil landform category *hummocky(>15%)*, are classified as *dissected* on the automated soil landform classification map, whereas lower lying areas between the hummocks are represented by category *level(0-10%)* characterized by a high concavity (Table 7.4). Sections of less concave or convex slopes are correctly classified as *hummocky(>15%)*.

The pattern of automatically classified soil landform categories, which represent category *hummocky-ridged(9-15%)* located in the center of the County of St.Paul soil landform map, is even more pronounced than the pattern representing

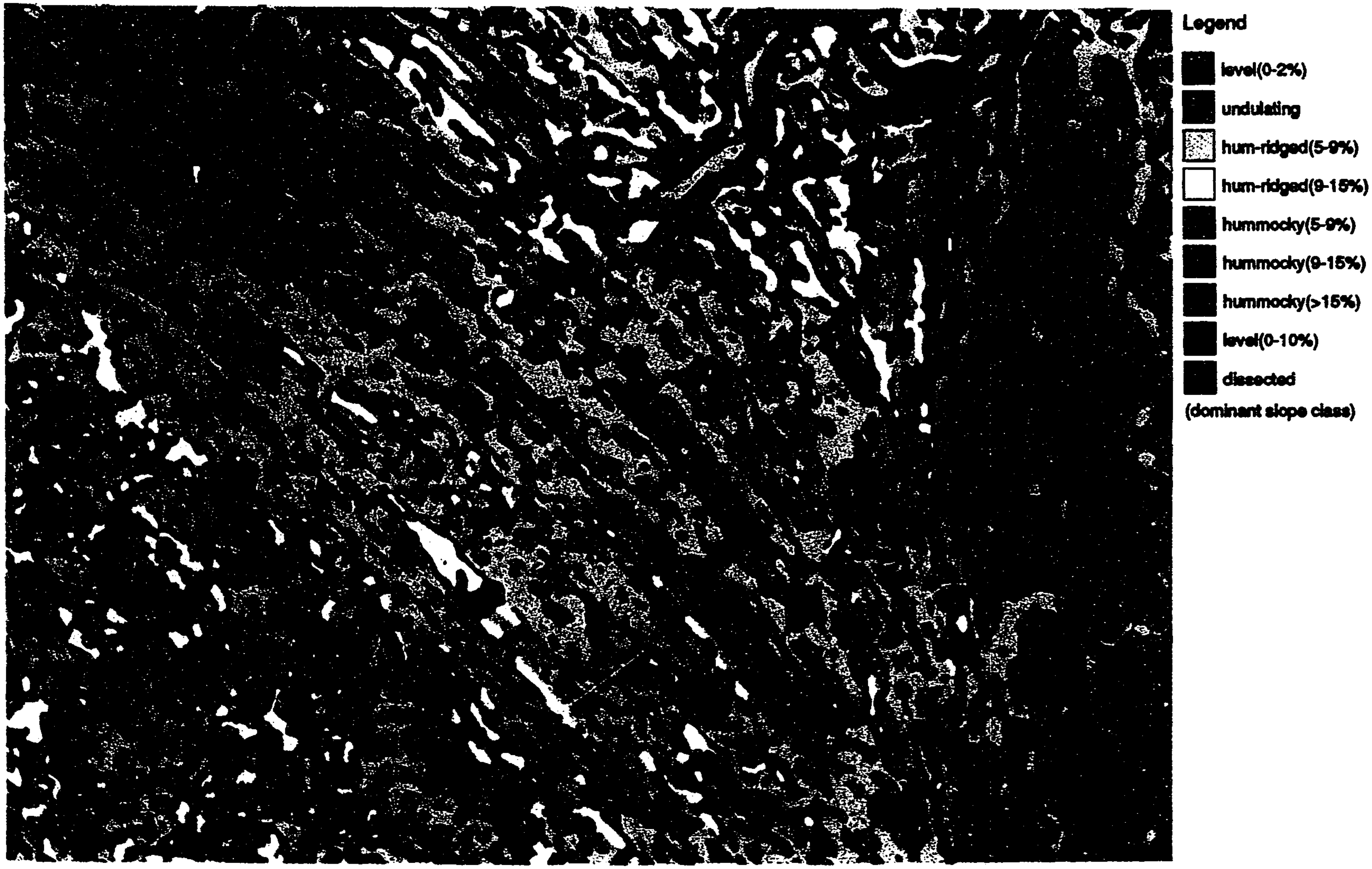


Figure 7.1. Automated soil landform classification based on supervised training field selection

7.3. Overlap of County of St.Paul Soil Landform Classification with Automated Soil Landform Classification

St.Paul soil categories	Automatically classified soil landform categories								
	2 Level	3 Level	5 Undul	7 Diss	10 HumRi	11 HumRi	12 Humm	13 Humm	14 Humm
1 Lake	**9225** **53.6**	1186 6.9	3494 20.3	11 0.1	2953 17.2	3 0.0		63 0.4	285 1.7%
2 Level(0-2%)	**23284** **29.3**	5537 7.0	27701 34.9	708 0.9	17482 22.0	225 0.3	762 1.0	1692 2.1	1985 2.5%
3 Level(0-10%)	49 0.3	**2423** **14.2**	1676 9.8	2437 14.3	6124 35.9	99 0.6	109 0.6	1601 9.4	2526 14.8%
4 Undulating(0-5%)	435 12.1		**2352** **65.5**		136 3.8		634 17.7	35 1.0	%
5 Undulating(2-5%)	13353 8.0	3423 2.1	**88110** **52.8**	1657 1.0	36407 21.8	1647 1.0	11998 7.2	6959 4.2	3234 1.9%
6 Dissected(>5%)				**964** **99.6**					4 0.4%
7 Dissected(>10%)		319 1.5		**13750** **64.8**	384 1.8	2649 12.5	106 0.5	818 3.9	3202 15.1%
8 Hum-Inclined(>9%)		674 22.6		358 12.0	34 1.1	355 11.9	3 0.1	348 11.7	**1208** **40.5%**
9 Hum-Inclined(>15%)		1285 24.8	193 3.7	548 10.6	461 8.9	229 4.4	12 0.2	707 13.6	**1749** **33.7%**
10 Hum-Ridged(5-9%)	215 0.4	4312 7.1	12554 20.8	255 0.4	**20550** **34.0**	1779 2.9	11713 19.4	7284 12.1	1782 3.0%
11 Hum-Ridged(9-15%)	48 0.5	1443 13.7	987 9.3	28 0.3	2640 25.0	**2317** **21.9**	939 8.9	1814 17.2	348 3.3%
12 Hummocky(5-9%)	1163 0.8	13761 9.4	26749 18.3	2745 1.9	43573 29.8	6880 4.7	**26326** **18.0**	20816 14.2	4383 3.0%
13 Hummocky(9-15%)	1298 0.9	28886 20.2	6951 4.9	7215 5.0	25194 17.6	13881 9.7	8419 5.9	**30387** **21.2**	20909 14.6%
14 Hummocky(>15%)	191 0.3	12604 20.2	817 1.3	9012 14.4	4785 7.7	6830 10.9	1092 1.8	10152 16.3	**16933** **27.1%**
15 Hummocky(5-15%)	20 1.2	163 9.8	**996** **60.0**		392 23.6		86 5.2	3 0.2	%

Overall class correspondence 32.60%

Numbers printed in bold represent the proposed dominant landform categories.

7.4. Percent Overlap of Automated Soil Landform Classification with Digital Terrain Model (DTM) Classes

Landform	**DTM classes**													
	Local relief(m)				Slope gradient(%)					Downslope curvature				
categories	0-1	1-3	3-10	>10	0-2	2-5	5-9	9-15	>15	vcv[1]	cv[2]	str[3]	cx[4]	vcx[5]
Level(0-2%)	87.3	12.8			100.						1.7	96.7	1.5	%
Level(0-10%)		3.5	82.5	14.0	18.7	40.0	40.5	0.8		1.9	56.9	22.9	17.3	1.1%
Undulating(2-5%)	9.1	76.0	14.9		94.5	5.5					8.0	86.1	5.9	%
Dissected(>10%)		0.1	3.9	96.0	2.6	7.4	18.3	49.2	22.5	13.2	28.6	16.1	34.7	7.4%
Hum-Ridged(5-9%)	0.7	33.5	65.7	0.1	55.4	44.3	0.4				32.1	44.4	23.4	%
Hum-Ridged(9-15%)		0.3	31.8	67.9	5.9	25.9	62.8	5.4		0.4	14.8	29.5	54.8	0.5%
Hummocky(5-9%)		0.5	99.2	0.3	8.4	90.9	0.8				9.4	77.6	13.0	%
Hummocky(9-15%)		1.4	91.7	7.0	14.5	67.6	17.7	0.2		0.5	25.2	34.4	39.5	0.4%
Hummocky(>15%)		0.8	41.7	57.6	11.6	26.2	38.8	20.1	3.3	6.9	42.9	13.3	28.5	8.4%

[1] very concave, [2] concave, [3] straight, [4] convex, [5] very convex

category *hummocky(>15%)*. The core of category *hummocky-ridged(9-15%)* is correctly classified as *hummocky-ridged(9-15%)* on the automated soil landform classification map, whereas the footslopes of the ridges are represented by category *level(0-10%)*. Category *level(0-10%)* represents areas of high concavity (Table 7.4) because training areas for the category were sampled along creeks and along floodplains of the Beaver River. Creeks, however, cannot always be unambiguously identified by the geometric signature of category *level(0-10%)* in the automated soil landform classification. Creeks, classified as *level(0-10%)* on the County of St.Paul soil landform map, are often narrower than the width provided by the squared neighbourhood size from which the contextual classifier is derived. For this reason, signatures of landform categories of lower relief and slope gradient magnitude surrounding the creeks often dilute the signature associated with creeks. Consequently, creeks are most often represented by landform categories of less pronounced relief and slope gradient magnitude, such as *hummocky-ridged(5-9%)*. For example, the surface expression of the St. Lina Creek on its course from the south of the study area to the Beaver River is nearly lost within *hummocky-ridged* and *hummocky* landform units because the surface expression of the creek smooths in with the surrounding landform features.

The same edge effect, which affects the creeks or any other narrow feature, is also visible on the automated soil landform classification map around Norberg and Bunder Lake classified as *level(0-2%)* in the automated soil landform classification, and other *level(0-2%)* categories located between *hummocky* and *hummocky-ridged* landform units. Towards the margins of these landform units, more and more grid points of higher relief magnitude are included within the neighbourhood because of the neighbourhood size of 275x275 meters. This edge effect causes the signatures of the morphometric class characteristics to change from *level(0-2%)* to *undulating(2-5%)* and further to *hummocky-ridged(5-9%)* the closer the grid cell is located towards the margin of *level(0-2%)* landform units.

Eyton (1993) and Wharton (1982) were aware of the edge effect caused by a contextual classifier derived for large neighbourhoods. Based on visual inspection of the classified maps, Eyton identified land use categories, which represented boundary areas, and joined these boundary categories with the remaining categories using a post-classification procedure based on the Mahalanobies distance (a statistical distance for group proximity). Since Eyton's classification was based on an unsupervised training field selection, the categories were determined according to a cluster analysis, which generates any predetermined number of categories. Consequently, some additional categories were created which represented only the boundary areas between the core areas of distinctive land uses. In this research, a supervised training field selection was used and categories, which represent the boundary areas in one instance, have a distinct meaning at another location. As a result, the landform units cannot be relabelled. To smooth out the edge effect, a majority filter for a convolved 5x5 neighbourhood was applied to this classification. The filtering process improved the overall impression of distinctive categories slightly but not sufficiently for aggregating smaller units to larger ones. The application of a post-processing region growing algorithm, as implemented by Weibel and DeLotto (1989), might prove to be an effective means for removing edge effects in future research.

Furthermore, the objective of this research was the grouping of composite landform elements to regions of *ridged* or *hummocky* landform patterns according to the requirements at ecosection level. However, the neighbourhood size was determined to be too small, to satisfy this objective. A single landform element was identified when instead the entire pattern of local landforms or a local landform should have been classified. In contrast, if the neighbourhood size had been increased, landform features, such as creeks, would have been even less likely labelled correctly by the geometric signature of category *level(0-10%)* because the edge effect would have been further intensified by widening the misclassified margins around the landform categories. Consequently, the selection of the neighbourhood size is a trade off between accuracy and generalization. The difficulty in satisfying both in a landform classification is caused by the fact that specific landforms only occur over a limited range of scales (Weibel and DeLotto, 1988).

7.5 Automated DTM Landform Classification

7.5.1 Classification Process

The objective of the second automated landform classification was to determine landform categories independently from the landform categories mapped on the County of St. Paul soil map (Brierley *et al.*, 1990) and the Sand River geology map (Andriashek and Fenton, 1989). Eight landform categories were selected as training areas for the automated DTM landform classification from a hillshaded-slope-gradient-overlay and a hillshaded-local-relief-overlay based on a synthesis of Canadian landform category definitions (Brierley *et al.*, 1990; E.C.S.S., 1987a; Andriashek and Fenton, 1989; Howes and Kenk, 1988) (Table A2.1 and A2.3). The categories used in the automated DTM landform classification were similar to those interpreted from DTM maps in Chapter 4 (Table 7.5). The categories, however, were differentiated predominantly on the basis of local relief and slope gradient class magnitudes and not on the basis of surface expression used as main selection criterion in the DTM landform interpretation.

The results of the quantitative analysis implemented in Chapter 6 indicates that categories of similar surface expression cannot be differentiated when they are represented by the same local relief and slope gradient magnitude. As a result, categories described as *rolling* and *hummocky-rolling of medium relief* in the DTM landform interpretation were combined as category *rolling* in the automated DTM landform classification (Table 7.5), and categories *hummocky-rolling of high relief* and *hummocky-ridged* of the DTM landform interpretation were combined as category *hummocky-rolling*. Furthermore, surface expression *dissected* was divided into the following two categories in the training field selection: first, *dissected 1* is associated with the Beaver River valley walls close to the floodplains and the lower less steep slopes of creek valleys represented by slope gradient of greater than 9 percent (Table 7.9); and, second, *dissected 2* corresponds with steep middle and upper convex slopes of the Beaver River drainage way represented by slope gradients of greater than 15 percent (Table7.9). Although automatically classified landform categories were selected according to quantitative modifiers, the categories were still labelled according to surface expression to provide a descriptive indicator for an increase in magnitude and variance of local relief and slope gradient. For example, *rolling* is associated with higher magnitude of local relief and slope gradient than *undulating*.

In the first discriminant analysis, the automated DTM landform classification showed a high overall correct classification of 90.06% which is much higher than the initial overall correct classification of 57.67% obtained in the first discriminant analysis of the automated soil landform classification. The improved discrimination of landform categories in the automated DTM landform classification can be explained by the selection of the categories according to differences in magnitudes of local relief and slope gradient. After removing misclassified observations, the

Table 7.5. Correspondence of Categories Selected for Automated DTM Landform Classification with Categories Selected for DTM Landform Interpretation

Landform Categories Selected for **Automated DTM Classification** (local relief, slope gradient)	**DTM Interpretation**
Level (0-1m, 0-2%)	Lake, Level
Undulating (1-3m, 0-2%)	Undulating
Rolling (3-10m, 2-5%)	Rolling, Hummocky-Rolling (medium relief)
Hummocky-Rolling (3-10m, 2-9%)	Hummocky-Rolling (high relief), Hummocky-Ridged
Ridged (>10m, 5-9%)	Ridged
Hummocky (>10m, 5-15%)	Hummocky
Dissected1 (>10m, >9%)	Dissected, Level
Dissected2 (>10m, >15%)	Dissected

Table 7.6. Classification Results of Automatically Generated DTM Landform Categories Based cn Supervised Training Field Selection According to DTM Landform Interpretation: Final Discriminant Analysis

Actual category membership (No. of observations)	**Predicted category membership**								
	1 Level	2 Undul	3 Roll	4 HuRo	5 Ridge	6 Hum	7 Diss1	8 Diss2	
1 Level(0-2%,0-1m) (390)	**390** **100.0**								%
2 Undulating(0-2%,1-3m) (394)		**394** **100.0**							%
3 Rolling(2-5%,3-10m) (564)		3 0.5	**561** **99.5**						%
4 Hum-Rolling(2-9%,3-10m) (937)			6 0.6	**854** **91.1**	61 6.5	16 1.7			%
5 Ridged(5-9%,>10m) (323)				28 8.7	**295** **91.3**				%
6 Hummocky(5-15%,>10m) (759)				13 1.7	29 3.8	**713** **93.9**	4 0.5		%
7 Dissected1(>9%,>10m) (71)							**71** **100.0**		%
8 Dissected2(>15%,>10m) (303)						6 2.0	6 2.0	**291** **96.0%**	

Overall correct classification 95.40%

correct classification improved to 95.04% in a second discriminant analysis (Table 7.6). Confusion is highest for categories *hummocky-rolling*(2-9%), *ridged*(5-9%) and *hummocky* (5-15%) because the slope gradient class ranges overlap for these categories.

7.5.2 Comparison of the Automated DTM Landform Classification with Manually Mapped Landform Classifications

The automated DTM landform classification (Figure 7.2) claims to be a generalized landform classification and therefore applicable to any land survey. To determine how well landform patterns are represented by the automated DTM landform classification, the classification was visually compared with the DTM landform map (transparency placed in a folder at the back of the thesis), the County of St.Paul soil landform map (Figure 3.5) and the Sand River geology landform map (Figure 3.4). Four main landform regions, which were also recognized on the other landform maps and the maps of physiographic units (Figure 3.2 and 3.3), are also apparent on the automated DTM landform classification map. In the east of the map, the terrain is classified as *level* and *undulating* representing low relief landform categories. The central portion of the map is covered by medium relief landform categories mainly represented by the category *rolling*, whereas the southwest of the map is mostly categorized as *hummocky-rolling* and *hummocky*. The Beaver River drainage way forms the fourth region represented by *dissected* and *hummocky* categories.

While the main landform regions coincide on all four landform maps, individual geology or soil landform categories are represented by several different landform categories on the automated landform classification map (Table 7.7 and 7.8) because the definitions of the landform categories differ between the classifications. However, the complex overlap between various landform categories, as apparent between the County of St. Paul soil landform classification and the automated soil landform classification, is greatly reduced on the automated DTM landform classification because fewer landform categories were used. The number of landform categories was reduced because the classification had to be as generalized as possible to apply to different land surveys. Consequently, specific categories, represented only by the geology or the soil landform classification, were not considered by the automated DTM landform classification. For this reason, an

Figure 7.2. Automated DTM landform classification based on supervised training field selection

Table 7.7. Overlap of County of St.Paul Soil Landform Classification with Automated DTM Landform Classification

St.Paul soil	**Automatically classified DTM landform categories**							
categories	Level	Undul[1]	Roll[2]	HuRo[3]	Ridged	Humm[4]	Diss1[5]	Diss2[5]
Lake	**8557**	3827	2910	1405	7	246		
	50.5	22.6	17.2	8.3	0.0	1.5		%
Level(0-2%)	21277	**28268**	18974	8654	389	1923	26	5
	26.8	**35.6**	23.9	10.9	0.5	2.4	0.0	0.0%
Level(0-10%)	20	2718	4738	**4826**	214	3598	90	1080
	0.1	15.7	27.4	**27.9**	1.2	20.8	0.5	6.3%
Undulating(0-5%)	331	**1708**	1522	31				
	9.2	**47.6**	42.4	0.9				%
Undulating(2-5%)	11367	**81654**	60052	12926	945	2407	194	1123
	6.7	**47.8**	35.2	7.6	0.6	1.4	0.1	0.7%
Dissected(>5%)						255	247	**466**
						26.3	25.5	**48.1%**
Dissected(>10%)			277	988	1375	**10295**	6338	2023
			1.3	4.6	6.5	**48.3**	29.8	9.5%
Hum-Inclined(>9%)			28	**1251**	142	1103	68	
			1.1	**48.3**	5.5	42.6	2.6	%
Hum-Inclined(>15%)	1	144	468	**2373**	62	2078	58	
	0.0	2.8	9.0	**45.8**	1.2	40.1	1.1	%
Hum-Ridged(5-9%)	100	8662	**37033**	12223	1504	1006		
	0.2	14.3	**61.2**	20.2	2.5	1.7		%
Hum-Ridged(9-15%)	40	772	**4117**	3431	1833	371		
	0.4	7.3	**39.0**	32.5	17.4	3.5		%
Hummocky(5-9%)	1062	18834	**81208**	39062	3615	6441	299	415
	0.7	12.5	**53.8**	25.9	2.4	4.3	0.2	0.3%
Hummocky(9-15%)	1090	5351	35566	**68988**	8913	23027	382	835
	0.8	3.7	24.7	**47.9**	6.2	16.0	0.3	0.6
Hummocky(>15%)	177	726	5402	**28061**	4722	20534	1604	1378
	0.3	1.2	8.6	**44.8**	7.5	32.8	2.6	2.2%
Hummocky(5-15%)	11	**1130**	385	134				
	0.7	**68.1**	23.2	8.1				%

Dominant landform categories are highlighted.

[1] Undulating, [2] Rolling, [3] Hummocky-Rolling, [4] Hummocky, [5] Dissected

Table 7.8. Overlap of Sand River Geology Landform Classification with Automated DTM Landform Classification

Geology	**Automatically classified DTM landform categories**							
categories	Level	Undul[1]	Roll[2]	HuRo[3]	Ridged	Humm[4]	Diss1[5]	Diss2[5]
Lake	**8574**	3611	2812	1484	19	172		
	51.4	21.7	16.9	8.9	0.1	0.1		%
Varied	81	2803	6485	9813	1429	11053	**12341**	9407
	0.2	5.3	12.1	18.4	2.7	20.7	**23.1**	17.6%
Terrace			744	910	932	**2617**	623	554
			11.7	14.3	14.6	**41.0**	9.8	8.7%
Flat	21450	**29569**	15340	7659	434	8679	710	1117
	25.2	**34.8**	18.1	9.0	0.6	10.2	0.8	1.3%
Flat-Hummocky(0-3m)	15628	**44765**	12207	750	796	222	40	
	21.0	**60.2**	16.4	1.0	1.1	0.3	0.1	%
Flat-Rolling(0-3m)	1913	**11254**	3156	268		55		10
	11.5	**67.6**	19.0	1.6		0.3		0.1%
Rolling(1-3m)	10312	**29721**	16853	6383	1078	4542	249	274
	14.9	**42.8**	24.3	9.2	1.5	6.5	0.4	0.4%
Rolling(3-10m)	3191	27928	**44225**	19640	4317	10541	1324	3754
	2.8	24.3	**38.5**	17.1	3.8	9.2	1.2	3.3%
Rolling(>10m)		50	3934	**7609**	3959	5293	389	514
		0.2	18.1	**35.0**	18.2	24.3	1.8	2.4%
Hummocky(1-3m)	41	228	134	297	118	**674**	137	11
	2.5	13.9	8.2	18.1	7.2	**41.1**	8.4	0.7%
Hummocky(3-10m)			69	298	222	**737**	28	130
			4.7	20.1	15.0	**49.7**	1.9	8.8%
Hummocky(>3m)	660	3109	19198	**60994**	6406	27750	316	223
	0.6	2.6	16.2	**51.4**	5.4	23.4	0.3	0.2%
Hum-Rolling(1-3m)	5852	**21908**	13338	4457	336	695	264	638
	12.3	**46.1**	28.1	9.4	0.7	1.5	0.6	1.3%
Hum-Rolling(1-10m)	4232	46657	**114499**	48092	5541	6311	586	1222
	1.9	20.5	**50.4**	21.2	2.4	2.8	0.3	0.5%
Hum-Rolling(3-10m)		90	1343	**3152**	1846	2580	493	36
		0.9	14.1	**33.0**	19.4	27.0	5.2	0.4%
Hum-Rolling(> 3m)			7	**971**	317	722	3	
			0.4	**48.1**	15.7	35.7	0.2	%
Hum-Rolling(> 10m)			8			106		**190**
			2.6			34.9		**62.5%**
Hum-Ridged(> 3m)	189	217	4805	**16722**	431	5080	12	
	0.7	0.8	17.5	**60.9**	1.6	18.5	0.0	%
Ridged(3-10m)		112	389	**542**	13	319	5	
		8.1	28.2	**39.3**	0.9	23.1	0.4	%
Ridge-Rolling(3-10m)	946	13315	**40068**	14799	3071	4865	166	1018
	1.2	17.0	**51.2**	18.9	3.9	6.2	0.2	1.3%

Dominant landform categories are highlighted.

[1] Undulating, [2] Rolling, [3] Hummocky-Rolling, [4] Hummocky, [5] Dissected

Table 7.9. Percent Overlap of Automated DTM Landform Classification with Digital Terrain Model (DTM) Classes

	DTM classes													
Landform categories	Local relief(m)				Slope gradient(%)					Downslope curvature				
	0-1	1-3	3-10	>10	0-2	2-5	5-9	9-15	>15	vcv[1]	cv[2]	str[3]	cx[4]	vcx[5]
Level	91.6	8.4			100.						1.3	97.4	1.3	%
Undulating	11.7	84.8	3.5		96.6	3.4					9.7	82.8	7.4	%
Rolling	0.5	22.3	77.0	0.2	45.7	53.9	0.4				21.0	61.5	17.4	%
Hum-Rolling		2.5	86.7	10.8	18.1	51.1	29.4	1.5		2.0	39.0	24.9	32.6	1.4%
Ridged			22.6	77.4	1.3	21.0	75.7	2.1		0.4	25.3	39.4	34.6	0.3%
Hummocky		0.4	22.9	76.7	8.1	21.7	37.2	31.3	1.8	7.3	38.8	14.2	35.1	4.6%
Dissected 1				100.	0.2	0.6	3.8	72.6	22.8	4.0	33.3	28.7	31.4	2.6%
Dissected 2		0.1	2.8	97.1	3.9	9.4	10.4	17.5	58.7	19.8	21.9	9.1	24.9	24.3%

[1] very concave, [2] concave, [3] straight, [4] convex, [5] very convex

overall class correspondence measure comparing the automated DTM landform classification with the soil or geology landform classification is not given.

The definitions of landform categories differ between the classifications because the categories of the DTM, soil and geology landform classifications were mainly differentiated on the basis of surface expression, whereas the categories of the automated DTM landform classification were mainly discriminated on the basis of morphometric classes. Consequently, the soil landform categories *hummocky* and *hummocky-inclined* of greater than 9 percent slope gradient and geology landform categories *hummocky-ridged*, *hummocky-rolling* and *hummocky* of greater than 3 meter local relief were all predominantly classified as *hummocky-rolling* in the automated DTM landform classification (Table 7.7 and 7.8). In contrast, soil and geology landform categories, which differ only according to their associated morphometric modifiers but are labelled by the same surface expression, are represented by different landform categories in the automated DTM landform classification. For example, *rolling(1-3m)* of the geology landform classification is associated with category *undulating* in the automated DTM landform classification, while *rolling(3-10m)* is associated with category *rolling* in the automated DTM landform classification, and, finally, category *rolling(>10m)* is associated with category *hummocky-rolling*. The same observation applies to most of the *hummocky*, *rolling* or *ridged* categories in the soil and geology landform classification except for category *hummocky(1-3m)* and *hummocky(3-10m)* in the geology landform classification. These categories were cut off at the margin of the map and only represent the smaller steeper portion of the landform unit as described in Chapter 6. For this reason, the categories are associated with automatically classified landform categories of higher than expected magnitude of relief and slope gradient, such as *hummocky* instead of *hummocky-rolling*.

Furthermore, soil landform category *level(0-2%)* and geology landform category *flat*, which represent predominantly lakes and poorly drained depressions, have a higher overlap with category *undulating* than with category *level* of the automated DTM landform classification. This unexpected overlap can be explained by two reasons: first, edge effects, as described in section 7.4.2., also occur in the automated DTM landform classification around lakes and other areas of low relief; and, second, *undulating* and *level* categories were defined slightly differently by the automated DTM landform classification than by the County of St.Paul soil landform classification. As shown in Chapter 6, the slope gradient class limits of the soil landform category *undulating(2-5%)* were overestimated in the County of St. Paul landform classification. For this reason, in the automated DTM landform classification, the categories *level* and *undulating* were differentiated on the basis of local relief only, whereas the slope gradient class limits (0 to 2% slope) remained the same for both classes. The change of the slope gradient class limits for *undulating* is justified by the high overlap of the County of St. Paul landform categories *undulating(0-5%)* and *undulating(2-5%)* with category *undulating* of the automated DTM landform classification.

While the morphometric class limits appeared to be underestimated for *undulating* in comparison to *level* in the automated DTM landform classification, the morphometric class limits associated with *dissected* 1 and 2 appear to be overestimated in the automated DTM landform classification. Most of the units classified as *dissected(>10%)* on the County of St. Paul soil map, are associated with *hummocky* rather than with *dissected* units on the automated DTM landform classification. The delineation of the category *dissected*, however, differs not only between the automated DTM landform classification and the County of St.Paul landform classification but also between the two automated landform classifications. On the automated DTM landform classification, the two *dissected* categories cover only narrow bands of steep slope portions along the Beaver River, whereas most of the river valley walls of less steep slopes are identified as *hummocky*. In contrast, on the automated soil landform classification, *dissected(>10%)* covers nearly the entire Beaver River valley walls which include also the less steep portions of the slopes. As a result, landform category *dissected(>10%)* of the automated soil landform classification interferes also with many other landform categories of the County of St.Paul soil landform classification (Table 7.3). In contrast, the interference of *dissected* with other categories is greatly reduced on the automated DTM landform classification.

The surface expression labels associated with the automatically classified landform categories may not correspond, in all instances, with the actual landform feature because landform categories are discriminated by the automated landform classification only on the basis of quantitative modifier frequency counts occurring within the closer proximity of a grid cell. For example, the Beaver River floodplains were classified as *hummocky-rolling* and *rolling*. The surface expression does not give any indication that the category represents floodplains; but both landform features, rolling hills and floodplains, consist predominantly of 3 to 10 meter local relief, 2 to

5 percent slope gradient and a majority of concave and convex slopes with a shift towards concavity (Table 7.9). Landform features of rolling hills or floodplains can only be differentiated according to their wider proximity and context in which they occur. Within their closer proximity, the landform categories are classified by the same numerical characteristics derived from a neighbourhood and can therefore not be differentiated by the automated classification process.

A similar effect applies also to single hummocks and ridges which are differentiated in a separate unit as *hummocky-rolling* within an area of *rolling* landforms located in the NE of the study area. These *hummocky* and *ridged* landform features were discriminated from the surrounding landform categories because the morphometric class frequency counts of these features exceeded the predetermined pattern of those frequency counts obtained for *rolling* landform categories. In the automated classification process, the context of a landform is fixed by the neighbourhood size and the frequency counts are limited to the morphometric measurements derived within that fixed neigbourhood. If the signature locally exceeds the predetermined frequency counts, the neighbourhood is placed into a different landform category. In contrast, a manual mapping process is flexible and can identify landforms of different sizes by their shape and morphometric modifier magnitude. Consequently, any automated landform classification still has to be interpreted and remapped subsequent to the initial automated mapping process as requested by Muehrcke (1972).

7.6 Summary and Future Research Considerations

The automated landform classification was implemented to integrate DTMs of local relief, slope gradient and downslope curvature in a multivariate, synthetic classification to generate new landform classification models. In this research, a contextual classifier consisting of morphometric class frequency counts obtained for neighbourhoods of fixed size was used in the automated classification of landforms. The two objectives of this classification were: first, to replicate as accurately as possible an existing specific landform classification based on landform categories delineated on the County of St.Paul soil map; and, second, to produce a landform classification which would be sufficiently generalized to be applicable to any Canadian land survey. Many of the County of St.Paul soil landform categories were represented by a multitude of landform categories in the automated soil landform classification because they were too similar according to morphometric class characteristics. For this reason, the landform categories could not be discriminated appropriately in a numerical classification. The inadequate discrimination of landform categories resulted in a heterogeneous pattern of landform units which is difficult to visualize and comprehend. As a result, interpretation and mapping is required subsequent to the initial classification.

The landform categories of the automated DTM landform classification were delineated from DTM image overlays according to morphometric characteristics and a synthesis of Canadian landform category definitions. The selection of the landform categories was based on the results derived from the quantitative analysis undertaken in Chapter 6 and of the DTM landform interpretation described in Chapter 4. Landform categories of larger areal extent than shown on the automated soil landform classification map were generated in the automated DTM landform classification because fewer landform categories were used and the change of landform characteristics were adjusted according to morphometric class differences. The disadvantage of the improved generalization was a loss in detail on the automated DTM landform classification map. But, generalization was given priority over accuracy in the automated DTM landform classification to improve the readability of the map and to allow the application of the landform classification in multiple land surveys.

The classification of landform regions containing landform patterns by simultaneously extracting single landform features of small areal extent was not achieved by this automated landform classification. This can be explained by the following two reasons: first, a fixed neighbourhood size does not conform with the varying scale of landform features and patterns; and, second, the computer has to be trained during the decision making process to analyse and classify the individual landform features and landform patterns in the same way as the human eye and brain interprets an image. During the process of image interpretation, the surface is perceived under a continuous series of transformations as the perceiver moves within a flexible array of dimensions (Zusne, 1970). As illustrated in this research, a contextual classifier based on frequency counts derived from neighbourhoods of a fixed size cannot differentiate between the varying scale of the landform features. One area for future research consideration is therefore to incorporate the complexity of perceptual invariance associated with visual interpretation (Zusne, 1970) into the quantitative decision making process. The quantitative decision making process has to rely on decision rules which consider a flexible array of dimensions. Numerous examples have been provided in image processing to segment the image into regions of varying neighbourhood sizes, such as region split and merge algorithms (Pavlidis, 1982; Cross *et al.*, 1988; Franklin and Wilson, 1991; 1992). Indeed, first attempts have been made to employ such algorithms in landform classification (Weibel, 1989; Dikau, 1990a) but future research is required to further develop and refine these approaches for the application in a contextual based landform classification.

8. Conclusions and Future Research Considerations

According to Dobson (1983), automation and spatial analysis serves as an integrated systems approach to geographic problem solving in which the problem is defined, the appropriate methods are chosen, and the tools are selected from a broad repertoire of automated and manual techniques. This thesis has presented an example of this approach to landform mapping, analysis, and classification. A number of manual, semiautomated and automated interpretation techniques were applied to digital terrain models (DTMs) to address the following two research objectives: first, to analyse an existing soil landform classification and geology landform classification to assess the accuracy and compatibility of those classifications and to determine suitable sets of morphometric modifiers which describe the landform categories quantitatively; and, second, to map and classify landform categories from DTMs defined according to Canadian landform classifications.

The research showed that DTMs can be used flexibly in qualitative as well as quantitative landform interpretation. Digital terrain models should supplement and, in some instances may replace, the airphotograph in landform mapping and classification projects. The following DTMs and DTM mapping products are recommended for use in visual interpretation of landforms. Classed elevation models are suitable for the delineation of broad physiographic units, whereas hillshaded models provide the most realistic representation of landform; hillshaded models should be used for the interpretation of surface expression. The possibility to interpret hillshaded models without seeing in three dimensions, the flexibility of the model, and the ability to combine the model with other data sources are three reasons for replacing airphotographs with DTMs. To add a quantitative modifier to the qualitative description of landform, the hillshaded model can be digitally overlaid with colour classed slope gradient and downslope curvature maps. Slope gradient has been identified as a more suitable morphometric modifier in landform classification than local relief because slope gradient can be determined more unambiguously than local [illegible] esearch results indicate that the selection of a neighbourhood size, from [illegible] ca relief is derived, poses a problem in the objective determination of local relief. Curvature proves to be the most suitable morphometric modifier for the identification of drainage patterns. But the areal extent of poorly drained depressions and lakes, which are of importance in soil and geology classification for locating organic material, could not be exactly delineated from classed curvature or slope gradient maps.

In this research, special emphasis was placed on the use of numerical techniques to provide an alternative to the subjective qualitative interpretation. Furthermore, the inclusion of context was a major component of the numerical techniques used for mapping and classifying landforms. For example, a modal filtering technique was applied to an extended neighbourhood(11x11) instead of to the immediate neighbourhood(3x3) for the generalization of DTM maps.

The selection of the neighbourhood size based on texture and grain analysis has always been a problem in context based mapping and classification. In this thesis, relative variance has been used for the first time as a texture measure for the determination of optimal neighbourhood sizes. The application of relative variance has the advantage over other texture measures because of its straight forward implementation, and because the threshold for acceptable homogeneity within a neighbourhood can be unambiguously determined. This threshold is formed by a logical breakpoint, at which the within neighbourhood variance becomes greater than the between neighbourhood variance. The use of relative variance to determine the optimal neighbourhood size according to the homogeneity measure of slope gradient distributions was useful; but problems do exist for the determination of neighbourhood sizes according to homogeneity measures of other DTM distributions, such as downslope curvature and elevation. Further research is required to test whether or not the relative variance can be used as a homogeneity measure to determine the grain of low relief landforms. In addition, relative variance tends to decrease with an increase of the sampling size and differs from area to area depending on the variability of present landforms. For this reason, the determination of the neighbourhood sizes for different regions of the study area is advised.

The implementation of an automated technique to classify categories of different landform assemblages was one of the most important objectives of the research. The principal problem in the implementation of an automated classification technique was the incorporation of context into the classification process. In this thesis, a context based classifier using morphometric class frequency counts was used for the first time in classifying landform. The method provides a first step in the attempt to build the human interpretation process into an automated interpretation model. The context based landform classification was a considerable improvement over classifications based on attribute homogeneity only, but the classification still showed some deficiencies. Edge effects and the incorrect discrimination between landform categories were the two main problems encountered on the classified landform maps. Two reasons suggested for the inadequate discrimination of landforms: first, the ability of the human eye/brain system to adjust the interpretation radius (neighbourhood) according to varying texture of different landforms was missing in the classification programs; and, second, the landform category training areas were selected according to qualitative descriptors instead of quantitative descriptors. To consider the varying texture of landform in the classification process, the determination of variable neighbourhood sizes has to be incorporated into future context based classification programs. Attempts have been made in image analysis research to provide a solution to the problem by developing region split and merge algorithms (Kettig and Landgrebe, 1976; Pavlidis, 1982; Cross *et al.*, 1988; Franklin and Wilson, 1991; 1992). The application of these techniques needs to be refined for future application in landform classification.

Additionally, the replacement of the qualitative interpretation technique with a quantitative interpretation technique, while at the same time maintaining the qualitative definition of landform categories, is not sufficient for the generation of a more objective and reliable landform classification. To make the landform category definitions amenable to numerical interpretation techniques, quantitative modifiers must be added to the qualitative landform category definitions. For example, *hummocky* landforms should also be differentiated from *rolling* landforms by selecting areas of steeper slope gradients, more pronounced curvature, relief of higher variation and multimodal rather than bimodal azimuth distributions.

In the future, these specific quantitative modifiers should also be added to the map legends to provide the user with a more accurate account of landform characteristics. The determination of quantitative modifiers in a post-classification analysis poses no problem if the data are available in digital form and if they are incorporated into a geographic information system. For the determination of quantitative modifiers in this thesis, the soil and geology landform categories were digitally overlaid with DTM distributions. The quantitative modifiers were then determined for each landform category from several DTM distributions in the form of statistical measures, such as the mode, the mean, and the variance. The standardized range provides a suitable measure for combining the mode, the mean and the variance into one parameter, if the number of quantitative modifiers must be reduced. Additionally, not every DTM distribution of local relief, slope gradient, azimuth, and curvature is of importance for the quantitative characterization of landform categories. Slope gradient, however, is the most appropriate variable for the representation of landform characteristics because the variance of slope gradient provides an additional indication for roughness of the landform. Curvature is only of importance if special emphasis is placed on the assessment of drainage patterns and the moisture content of soil or surficial materials.

A post classification analysis also provides a method of assessing the accuracy of predefined landform category definitions by comparing the predefined landform category definitions with the landform characteristics of the mapped landform categories. This assessment is of special importance when other parameters, such as material modifiers, have been incorporated into an integrated systems approach for mapping soil or geology categories, and when the boundaries of the soil and geology polygons have been adjusted to fit the boundaries of all of the parameters integrated in the classification. Clearly, such a detailed assessment was not implemented after the final compilation of the County of St. Paul soil survey and Sand River geology survey map, because the quantitative modifiers of several landform categories did not coincide with those determined from associated DTM distributions. Furthermore, the comparison of the soil and geology landform classifications showed that the landform categories on the maps varied between the two classifications, although the definitions of the landform categories were in many respects compatible. This result confirms the need for a more rigidly defined landform classification and the need for reliable interpretation and classification techniques.

The automated landform classification presented in this thesis provided an approach to integrate various classed DTM distributions in a multivariate classification process. The formation of comprehensive landform categories as proposed for Canadian Ecological Land Classifications was the objective of the classification process. The classification implemented in this thesis, however, has been restricted to the classification of form only. In future research projects, other parameters related to material and process modifiers should be incorporated into the multivariate classification. The integration of these parameters into a landform model may allow the prediction of genetically defined landform categories as used in Canadian terrain classification systems and the Canadian Soil Landform Classification. An increase in the number of components incorporated into the classification, however, increases the complexity of the modelling process, particularly when spatial dependency measurements required for the consideration of context information are included in the analysis. In this thesis, difficulties arose in determining neighbourhood sizes for the classification of landform categories because neighbourhood sizes changed according to landform variability and according to different morphometric variable distributions. If material and process parameters are included in the automated modelling process, problems associated with the measurement of varying spatial dependencies will be even more difficult to solve.

While the human analyst is flexible in making inferences about context and attribute relationships based on knowledge and expertise, the computer has to be trained by setting up rules for each assumption leading to a decision. Computer capabilities would be exhausted if all of the assumptions made by the human analyst were built into a program. Consequently, human input and interaction during the modelling process is necessary to produce a meaningful landform map. The research results suggest that the computer is an indispensable tool for transforming and displaying landform data objectively and efficiently; but as stated by Imhof (1982), the insight into problem formation, the interpretation of results and the final judgement about the content and the design of a map remains the critical work of the human analyst.

References

Ahnert, F. 1970. An approach towards a descriptive classification of slopes. *Zeitschrift fur Geomorphologie*, N. F. Supplement Band 9: 70-84.

Alberta Bureau of Surveying and Mapping and Resource Evaluation and Planning Division, 1985. *Specifications and Procedures Manual: 1:20,000 Digital Base Mapping Project*. Energy, Mines and Natural Resources.

Andriashek, L.D. and M.M. Fenton 1989. *Quarternary Stratigraphy and Surficial Geology of the Sand River Area 73L*. Alberta Research Council Bulletin No. 57, Edmonton.

Bahrenberg, G. and E. Giese 1975. *Statistische Methoden und ihre Anwendung in der Geographie*. Teubner Studienbucher, Stuttgart.

Band, L.E. 1986. Topographic partition of watersheds with digital elevation models. *Water Resources Research* 22 (1): 15-24.

Barnett, D.M., S.A. Edlund, and L.A. Dredge 1977. *Terrain Characterization and Evaluation: an Example from Eastern Melville Island*. Energy, Mines and Resources Canada, Geological Survey of Canada Paper 76-23.

Barsch, D. and H. Liedtke 1980. Principles, scientific value and practical applicability of the geomorphological map of the Federal Republic of Germany at the scale of 1:25000 (GMK 25) and 1:100000 (GMK 100). *Zeitschrift fur Geomorphologie*, N. F. Supplementband 36: 296-313.

Barsch, D. and G. Staeblein 1989. Geomorphological mapping in the Federal Republic of Germany: The GMK 25 and the GMK 100. *Catena* Supplement 15: 343-347.

Beckett, P.H.T. and P.A. Burrough 1971. The relation between cost and utility in soil survey IV: comparison of the utilities of soil maps produced by different survey procedures, and of different scales. *Journal of Soil Science* 22 (4): 466-480.

Beckett, P.H.T. and R. Webster 1971. Soil variability: a review. *Soils and Fertilizers* 34 (1): 1-15.

Bell, J.C., R.L. Cunningham, and G.W. Peterson 1990. Soil resource data based generation using soil landscape models. *GIS for the 1990's*, Conference Proceedings, Canadian Institute of Surveying and Mapping: 745-758.

Bie, S.W. and P.H.T. Beckett 1971. Quality control in soil survey introduction: I. the choice of mapping units. *Journal of Soil Science* 22 (1): 32-49.

Brassel, K. E. and R. Weibel 1988. A review and framework of automated map generalization. *International Journal of Geographical Information Systems* 2 (3): 229-44.

Brierley, J.A., L.D. Andriashek, and W.L. Nikiforuk 1990. *Soil Survey of the County of St. Paul, Alberta*. Alberta Preliminary Soil Survey Report No. 52.

Brink, A.B.A., J.A. Mabbutt, J.A. Webster, and P.H.T. Beckett 1966. *Report of the Working Group on Land Classification and Data Storage of Terrain Data*. Military Engineering Experiment Establishment, Christchurch, Report 940.

Burgess, T.M. and R. Webster 1980a. Optimal interpolation and isarithmic mapping I: The semivariogram and punctual kriging. *Journal of Soil Science* 31: 315-32.

Burgess, T.M. and R. Webster 1980b. Optimal interpolation and isarithmic mapping II: Block kriging. *Journal of Soil Science* 31: 333-42.

Burrough, P.A. 1986. *Principles of Geographical Information Systems for Land Resources Assessment*. Clarendon Press, Oxford.

Canada Committee on Ecological Land Classification (CCELC) 1976. Summary of business sessions. *Ecological Land Classification Series 1*, Proceedings of the first meeting, Land Directorate Environment Canada, Ottawa: ix-xii.

Carrara, A. 1983. Multivariate models for landslide hazard evaluation. *Mathematical Geology* 15 (3): 403-426.

Catanzariti, E. and A. Mackworth 1978. Forests and pyramids: using image hierarchies to understand Landsat images. *Proceedings of the 5th Canadian Symposium on Remote Sensing*, Victoria, 1978: 284-291.

Chorovicz, J., J. Kim, S. Manoussis, J.-P. Rudant, P. Foin, and I. Veillet 1989. A new technique for recognition of geological and geomorphological patterns in DTM's. *Remote Sensing of Environment* 29: 229-239.

Christian, C.S. and G.A. Stewart 1968. Methodology of integrated surveys in aerial surveys and integrated studies. *Proceedings Toulouse Conference 1964 Unesco*, Paris: 233-280.

Clark, J.S. 1976. Soil surveys in the Canada Department of Agriculture. *Ecological Land Classification Series* 1: 51-53.

Clerici, A. 1980. A method for drawing slope maps from contour maps by automatic data acquisition and processing. *Computers and Geosciences* 6: 289-297.

Cooke, R.U. and J.C. Doornkamp 1974. Geomorphological mapping. In R.U. Cooke and J.C. Doornkamp (eds.), *Geomorphology in Environmental Management*, Clarendon Press, Oxford: 352-379.

Cooke, R.U. and J.C. Doornkamp 1990. Mapping geomorphology. In R.U. Cooke and J.C. Doornkamp (eds.), *Geomorphology in Environmental Management*, 2nd edition, Clarendon Press, Oxford: 19-63.

Cross, A.M., D.C. Mason, and S.J. Dury 1988. Segmentation of remotely sensed images by split-and-merge process. *International Journal of Remote Sensing* 9 (8): 1329-1345.

Dalrymple, J.B., R.J. Blong, and A.J. Conacher 1968. A hypothetical nine unit landsurface model. *Zeitschrift fur Geomorphologie* N. F. 12 (1): 60-76.

Davis, J.C. 1986. *Statistics and Data Analysis in Geology*. John Wiley & Sons, 2nd edition.

Department of Geography 1989a. *GEODIGIT, Digitizing and Surfacing Package for Inhouse Use*. Department of Geography, University of Alberta, Edmonton, Alberta.

Department of Geography 1989b. *VEC2RAS, Vector to Raster Conversion Package for Inhouse Use*. Department of Geography, University of Alberta, Edmonton, Alberta.

Dikau, R. 1989. The application of a digital relief model to landform analysis in geomorphology. In J. Raper (ed), *Three Dimensional Applications in Geographical Information Systems*, Taylor & Francis, London: 51-78.

Dikau, R. 1990a. Geomorphic landform modelling based on hierarchy theory. *4th International Symposium on Spatial Data Handling*, July 23-27, Zurich: 230-239.

Dikau, R. 1990b. Derivatives from detailed geoscientific maps using computer methods. *Zeitschrift fur Geomorphologie*, N.F., Suppl.Bd. 80: 45-55.

Dobson, M.W. 1973. Choropleth maps without class intervals?: a comment. *Geo Analysis* 4: 358-360.

Dobson, J.E. 1983. Automated geography. *The Professional Geographer* 35 (2): 135-142.

Donker, N.H. and A.M. Meijerink 1977. Digital processing of Landsat imagery to produce a maximum impression of terrain ruggedness. *ITC Journal* 4: 683-703.

Douglas, D.H. 1987. Experiments to locate ridges and channels to create a new type of digital elevation model. *The Canadian Surveyor* 41 (3): 373-406.

Dumanski, J., B. Klosterman, and S.E. Brandon 1975. Concepts, objectives and structure of the Canadian Soil Information System. *Canadian Journal of Soil Science* 55: 181-187.

Elghazali, M.S. and M.M. Hassan 1986. A simplified terrain relief classification from DEM data using finite differences. *Geo-Processing* 3: 167-178.

Evans, I.S. 1972. General geomorphometry, derivatives of altitude, and descriptive statistics. In R.J. Chorley (ed), *Spatial Analysis in Geomorphology*. Methuen, London: 17-90.

Evans, I.S. 1976. The selection of class intervals. *Transactions of the Institute of British Geographers*, NS 2: 98-124.

Evans, I.S. 1980. An integrated system of terrain analysis and slope mapping. *Zeitschrift fur Geomorphologie* N. F., Supplementband 36: 274-295.

Evans, I.S. 1981. General geomorphometry. In A.S. Goudie (ed), *Manual of Techniques in Geomorphology*. Unwin, London, 1st edition: 31-37.

Evans, I.S. 1987. The morphometry of specific landforms. In V. Gardiner (ed.), *International Geomorphology 1986 Part II*, John Wiley & Sons Ltd: 105-124.

Expert Committee on Soil Survey (E.C.S.S.) 1987a. *The Canadian System of Soil Classification*. Research Branch, Canada Department of Agriculture, Publ. 1646, Ottawa.

Expert Committee on Soil Survey (E.C.S.S.) 1987b. *Soil Survey Handbook, Volume I.* Agriculture Canada, Research Branch, Technical Bulletin 1987-9E, Edmonton.

Eyton, J.R. 1974. *An Analytical Surfacing Methodology for Application to the Geometric Measurement and Analysis of Landforms*. Ph.D. Thesis, University of Illinois, Urbana.

Eyton, J.R. 1984. Raster contouring. *Geo Processing* 2: 221-242.

Eyton, J.R. 1990. Color stereoscopic effect cartography. *Cartographica* 27 (1): 20-29.

Eyton, J.R. 1991. Rate of Change Maps. *Cartography and GIS's* 18 (2): 87-103.

Eyton, J.R. 1992. *TERRA FIRMA, a display and analysis package*. Department of Geography, University of Alberta, Edmonton, Alberta.

Eyton, J.R. 1993. Urban land use classification and modelling using cover-type frequencies. *Applied Geography*, forthcoming in 13(2).

Fenton, M.M. and L.D. Andriashek 1983. *Surficial Geology of the Sand River Area, Alberta*. Alberta Research Council, Edmonton.

Fisher, R.A. 1936. The use of multiple measurements in taxonomic problems. *Annals of Eugenics* 7: 179-188.

Franklin, S.E. 1987. Geomorphometric processing of digital elevation models. *Computers and Geosciences* 13 (6): 603-609.

Franklin, S.E. and Peddle, D.R. 1987. Texture analysis of digital image data using spatial coocurrence. *Computers and Geosciences* 13 (3): 293-311.

Franklin, S.E. and B.A. Wilson 1991. Spatial and spectral classification of remote sensing imagery. *Computers and Geosciences* 17 (8): 1151-1172.

Franklin, S.E. and B.A. Wilson 1992. A three stage classifier for remote sensing of mountain environments. *Photogrammetric Engineering and Remote Sensing* 58 (4): 449-454.

Fu, K.S. 1982. *Syntactic Pattern Recognition, Applications*. Springer Verlag, Heidelberg.

Fulton, R.J. and N.F. Alley 1974. Terrain analysis; legend used in British Columbia. *Ecological Land Classification Series*, 0: 15-21.

Fulton, R.J., A.N. Boydell, D.M. Barnett, D.A. Hodgson, and V.N. Rampton 1974. Terrain mapping in northern environments. *Ecological Land Classification Series* 0: 3-14.

Gardiner, V. 1976. Land evaluation and the numerical delimitation of natural regions. *Geografica Polonica* 34: 11-30.

Gardiner, V. and K.J. Gregory 1977. Progress in portraying the physical landscape. *Progress in Physical Geography* 1 (1): 1-22.

Gong, P. and P.J. Howarth 1992. Frequency-based contextual classification and gray-level vector reduction for land-use identification. *Photogrammetric Engineering and Remote Sensing*, 58 (4): 423-437.

Goodchild, M.F., and D.M. Mark 1987. The fractal nature of geographic phenomena. *Annals of the Association of American Geographers* 77 (2): 265-278.

Goodchild, M.F. 1992. Geography and statisticians. *The Operational Geographer* 10 (2): 3-7.

Grant, K. 1975. *The PUCE Programme for Terrain Evaluation for Engineering Purposes*. I. Principles. CSIRO Division Applied Geomechanics Technical Paper 15.

Gregory, K.J. and E.H. Brown 1966. Data processing and the study of landform. *Zeitschrift fur Geomorphologie* 10 (3): 237-263.

Grigg, D. 1967. Regions, models and classes. In R.J. Chorley and P. Haggett (eds), *Models in Geography*, Methuen, London: 461-509.

Gutersohn, H. 1932. *Relief und Flussdichte*. Ph.D. Dissertation, Universitat Zurich.

Haralick, R.M., K. Shanmugam, and I. Dinstein 1973. Textural features for image classification. *IEEE Transactions on Systems, Man and Cybernetics*: 610-621.

Haralick, R.M. and K. Shanmugam 1974. Combined spectral and spatial processing of ERTS imagery data. *Remote Sensing of the Environment* 3: 3-13.

Hardy, R.L. 1971. Multiquadric equations of topography and other irregular surfaces. *Journal of Geophysical Research* 76 (8): 1905-1914.

Harris, R. 1980. Spectral and spatial image processing for remote sensing. *International Journal of Remote Sensing* 1 (4): 361-375.

Hills, G.A. 1976. An integrated iterative holistic approach to ecosystem classification. *Ecological Land Classification Series* 1: 73-97.

Horn, B.K.P. 1982. Hillshading and the reflectance map. *Geo Processing* 2: 65-144.

Horvath, E.H., E.A. Fosnight, A.A. Klingebiel, D.G. Moore, and J.E. Stone 1987. Using a spatial and tabular database to generate statistics from terrain and spectral data for soil surveys. *Soil Survey Techniques, Soil Science Society of America Special Publication* 20: 91-99.

Howes, D.E. and E. Kenk 1988. *Terrain Classification System for British Columbia*. MOE Manual 10. Ministry of Environment, Victoria.

Imhof, E. 1982. *Cartographic Relief Presentation*. Walter De Gruyter, Berlin.

Isachenko, A.G. 1973. *Principles of Landscape Science and Physical Geographic Regionalization*. Melbourne University Press.

Jenks, G.F. and D.S. Know 1961. The use of shading patterns in graded series. *Annals of the Association American Geographers* 51 (3): 316-334.

Jensen, J.R. 1986. *Introductory Digital Image Processing, A Remote Sensing Perspective*. Prentice Hall, NJ.

Johnson, V.A. 1988. *Digital Terrain Modelling Applied to the Alberta 1:20000 Mapping Project*. Unpublished M.Sc. Thesis, Department of Geography, University of Alberta.

Jones, N. 1982. The formation of glacial flutings in east-central Alberta. In R. Davidson-Arnott, W. Nickling, and B.D. Fahey (eds), *Research in Glacial, Glaciofluvial and Gaciolacustrine Systems*. Proceedings 6th Guelph Symposium on Geomorphology 1980, Geo Books, Norwich: 49-70.

Judd, D.D. 1986. Processing techniques for the production of an experimental computer generated shaded-relief map. *The American Cartographer* 13 (1): 722-79.

Keates, J.S. 1989. *Cartographic Design and Production*. Longman, Harlow Essex, 2nd edition.

Kettig, R.L. and D.A. Landgrebe 1976. Classification of multispectral image data by extraction and classification of homogeneous objects. *IEEE Transaction on Geoscience Electronics* GE-14 (1): 19-26.

Klimaszewski, M. 1988. On constructing detailed geomorphological maps. *Zeitschrift fur Geomorphologie* N. F. 32 (4): 457-470.

Klingebiel, A.A., E.H. Horvath, D.G. Moore, and W.U. Reybold 1987. Use of slope, aspect and elevation maps derived from digital elevation model data in making soil surveys. *Soil Survey Techniques, Soil Science Society of America Special Publication* 20: 77-90.

Kocaoglu, S.S. 1975. *Reconnaissance Soil Survey of the Sand River Area (73L).* Alberta Institute of Pedology Report No. S-74-34, University of Alberta Bulletin N.SS 15, Edmonton.

Koestli, A. and E. Wild 1984. A digital elevation model featuring varying grid size. *Commission III, ISP-Congress*, Rio de Janeiro.

Kraak, M.J. 1989. Computer-assisted cartographical 3D imaging techniques. In J. Raper (ed), *Three Dimensional Applications in Geographic Information Systems*, Taylor & Francis, London: 99-114.

Kundert, K. 1988. *Untersuchungen zur automatischen Klassifikation von raumlichen Einheiten*. Unpublished MS thesis, Department of Geography, University of Zurich.

Lacate, D.S. 1969. *Guidelines for Bio-Physical Land Classification*. Department of Fisheries and Forestry, Canadian Forestry Service, Publication No.1264, Ottawa.

Land Information Services Division 1985. *The 1:20,000 Base Mapping Project Specification and Procedures Manual.* Alberta Forestry Lands and Wildlife, Edmonton.

Landgrebe, D.A. 1980. The development of a spectral-spatial classification for earth observational data. *Pattern Recognition* 12: 165-175.

Laut, P. and T.A. Paine 1982. A step towards an objective procedure for land classification and mapping. *Applied Geography* 2: 109-126.

Leser, H. 1978. *Landschaftsokologie*. UTM, Stuttgart.

Lillesand, T.M. and R.W. Kiefer 1987. *Remote Sensing and Image Interpretation*. Wiley, New York.

Mabbutt, J.A. 1968. Review of concepts of land classification. In G.A. Stewart (ed), *Land Evaluation*, Macmillan, Melbourne: 11-28.

Mark, D.M. 1975. Geomorphometric parameters: a review and evaluation. *Geografiska Annaler* 57A (3-4): 165-177.

Mark, D.M. 1979. Phenomenon-based-structuring and digital terrain modelling. *Geo-Processing* 1: 27-36.

Mark, D.M. 1984. Automated detection of drainage networks from digital elevation models. *Cartographica* 21: 168-178.

Mark, D.M. and P.B. Aronson 1984. Scale-dependent fractal dimensions of topographic surfaces. An empirical investigation with applications in geomorphology and computer mapping. *Mathematical Geology* 16 (7): 671-683.

Mather, P.M. 1972. Areal classification in geomorphology. In R.J. Chorley (ed), *Spatial Analysis in Geomorphology*, Harper & Row, London: 305-322.

McLaren, R.A. and T.J.M. Kennie 1989. Visualisation of digital terrain models: techniques and applications. In J. Raper (ed), *Three Dimensional Application in Geographical Information Systems*. Taylor & Francis, London: 79-98.

Mitchell, C.W. 1973. *Terrain Evaluation*. Longman, London, 1st edition.

Mitchell, C.W. 1991. *Terrain Evaluation*. Wiley & Sons, New York, 2nd edition.

Moellering, H. and A.J. Kimerling 1990. A new digital slope-aspect display process. *Cartography and GIS's* 17 (2): 151-159.

Monmonier, M. 1977. *Maps, Distortions and Meaning*. Association of American Geographers, Resource Paper No.75-4, Washington D.C.

Muehrcke, P. 1972. *Thematic Cartography*. Association of American Geographers, Resource Paper No.19, Washington D.C.

Niemann, K.O. 1988. *DEM Drainage as Ancillary Data to Enhance Digital LANDSAT Classification Accuracies.* Unpubl. Ph.D. thesis, University of Alberta, Department of Geography, Edmonton.

Oliver, M.A. and R. Webster 1986. Semi-variograms for modelling the spatial patterns of landforms and soil properties. *Earth Surface Processes and Landform* 11: 491-504.

Ollier, C.D. 1977. Terrain classification: methods, applications and principles. In J.R. Hails (ed), *Applied Geomorphology*, Elsevier: 277-316.

O'Neill, M.P. and D.M. Mark 1987. On the frequency distribution of land slope. *Earth Surface Processes and Landforms* 12: 127-136.

Onorati, G., M. Poscolieri, R. Ventura, V. Chiarini, U. Crucilla 1992. The digital elevation model of Italy for geomorphology and structural geology. *Catena* 19: 147-178.

Oswald, H. and H. Raetzsch 1984. A system for generation and display of digital elevation models. *Geo Processing* 2: 197-218.

Papo, H.B. and E. Gelbman 1984. Digital terrain models for slopes and curvatures. *Photogrammetric Engineering and Remote Sensing*, 50 (6): 695-701.

Parry, J.T. and J.A. Beswick 1973. The application of two morphometric terrain classification systems using airphoto interpretation methods. *Photogrammetria* 29 (5): 153-186.

Partsch, J. 1911. *Schlesien, eine Landskunde fur das deutsche Volk II.* Breslau.

Pavlidis, T. 1982. *Algorithms for Graphics and Image Processing.* Computer Science Press, Rocheville, MD.

Pennock, D.J., B.J. Zebarth and E. DeJong 1987. Landform classification and soil distribution in hummocky terrain, Sasketchewan, Canada. *Geoderma* 40: 297-315.

Peucker, T.K., R.J. Fowler, J.J Little, and D.M. Mark 1976. *Triangulated Irregular Networks for Representing Three-Dimensional Surfaces.* Technical Report Number 10, Geographical Data Structures Project, CNR Contract N00014-75-C-0886.

Peucker, T.K. 1980. The use of computer graphics for displaying data in three dimensions. *Cartographica* 17 (2): 73-95.

Peuquet, D.J. 1979. Raster processing: an alternative approach to automated cartographic data handling. *American Cartographer* 6 (2): 129-139.

Pike, R.J. and W.J. Rozema 1975. Spectral analysis of landforms. *Annals of the Association of the American Geographer* 65 (4): 499-515.

Pike, R.J. 1988. The geometric signature: quantifying landslide-terrain types from digital elevation models. *Mathematical Geology* 20 (5): 491-511.

Pike, R.J., W. Acevedo, and D.H. Card 1989. Topographic grain automated from digital elevation models. *Autocarto* 9: 128-137.

Pike, R.J. and G.P. Thelin 1989. Cartographic analysis of U.S. topography from digital data. *Autocarto* 9: 631-639.

Rains, B., J. Shaw, R. Skoye, D. Sjogren, and D. Kvill in press. The late Wisconsin subglacial mega flood paths in Alberta. forthcoming in *Geology*.

Rayner, J.N. 1971. *An Introduction to Spectral Analysis*. Pion, London.

Robinson A., R. Sale, J. Morrison 1978. *Elements of Cartography*. Wiley & Sons, New York, 4th edition.

Rowe, J.S. 1971. Why classify forest land? *Forestry Chronicle* (June): 144-148.

Rowe, J.S. and J.W. Sheard 1981. Ecological land classification: a survey approach. *Environmental Management* 5 (5): 451-464.

Savigear, R.A.G. 1965. A technique of morphological mapping. *Annals of the Association of American Geographers* 55: 516-519.

Schmid, G. 1987. *Ein methodischer Ansatz zur Auswertung naturraumlicher Einheiten mittels digitaler Gelandemodelle und Landsat-MSS-Daten am Beispiel des Mount Allan, kanadische Rocky Mountains.* Unpublished Diplom thesis, Department of Geography, Philipps-University, Marburg.

Schowengerdt, R. 1983. *Techniques for Image Processing and Classification in Remote Sensing.* Academic Press, Toronto.

Siegel, S. 1956. *Nonparametric Statistics for the Behavioral Sciences.* McGraw-Hill Books, New York.

Smith, J.W.F. and I.A. Campbell 1989. Error in polygon overlay processing of geomorphic data. *Earth Surface and Processes and Landforms* 14: 703-717.

Speight, J.G. 1968. Parametric description of landform. In G.A. Stewart (ed), *Land Evaluation*, Macmillan, Melbourne: 239-250.

Speight, J.G. 1974. A parametric approach to landform regions. *Special Publication of the Institute of British Geographers* 7: 213-230.

Speight, J.G. 1976. Numerical classification of landform elements from airphoto data. *Zeitschrift fur Geomorphologie N.F.*, Supplementband 25: 154-168.

SPSS Inc. 1986. *SPSSX User's Guide.* 2nd edition, McGraw Hill Book Company.

Starr, D.W. and A.K. Mackworth 1978. Exploiting spectral, spatial and semantic constraints in the segmentation of Landsat images. *Canadian Journal of Remote Sensing* 4 (2): 101-107.

Strahler, A.N. 1950. Equilibrium theory of erosional slopes approached by frequency distribution analysis. *American Journal of Science* 248: 673-696.

Strahler, A.N. 1956. Quantitative slope analysis. *Bulletin of the Geological Society of America* 67: 571-606.

Strobl, J. 1988. Einige Aspekte geomorphologischer Analyse and Dokumentation aus der Sicht der EDV. *Zeitschrift fur Geomorphologie N.F.*, Supplementband 68: 9-19.

Tanimoto, S.L. and T. Pavlidis 1975. A hierarchical data structure for picture processing. *Computer Graphics and Image Processing* 4 (2): 104-119.

Thie, J., N. Chartrand, and G.F. Mills 1979. Interpretation of an ecological data base using the Canada Land Data System. *Ecological Land Classification Series* 7: 351-357.

Thomas, I.L. 1980. Spatial postprocessing of spectrally classified Landsat data. *Photogrammetric Engineering and Remote Sensing* 46 (9): 1201-1206.

Tobler, W.R. (ed) 1970. *Selected Computer Programs*. Department of Geography, University of Michigan, Ann Arbor, MI.

Tobler, W.R. 1973. Choropleth maps without class intervals? *Geo Analysis* 3: 262-265.

Tomlinson, R.F., H.W. Calkins and D.F. Marble 1976. *Computer Handling of Geographical Data: An Examination of Selected Geographical Information Systems*. Unesco, Paris.

Toomey, M.A.G. 1986. Alberta digital elevation model. *Commission III, ISP Congress*, March 1986.

Toomey, M.A.G. 1988. Digital elevation models in Alberta. *Commission ISPRS Conference*, July 1988 in Kyoto, Japan.

Valentine, K.W.G. 1986. *Soil Resource Surveys for Forestry*. Monography on Soil Resource Survey 10, Clarendon Press, Oxford.

Van Zuidam, R.A. 1986. *Aerial Photo-Interpretation in Terrain Analysis and Geomorphological Mapping*. Smits Publishers, The Hague.

Verstappen, H.T. 1977. *Remote Sensing in Geomorphology*. Elsevier, Amsterdam.

Verstappen, H.T. 1983. *Applied Geomorphology*. Geomorphological Survey for Environmental Development. Elsevier, Amsterdam.

Vink, A.P.A. 1983. *Landscape Ecology and Land Use*. Longman, London.

Walsh, S.J., D.R. Lightfood, and D.R. Butler 1987. Recognition and assessment of error in geographic information systems. *Photogrammetric Engineering and Remote Sensing* 53(10): 1423-1430.

Way, D.S. 1973. *Terrain Analysis: A Guide to Site Selection Using Aereal Photographic Interpretation*. Dowden, Hutchinson & Ross, Stroudsburg, Pennsylvania.

Webster, R. and P.H.T. Beckett 1970. Terrain classification and evaluation using airphotography: a review of recent work at Oxford. *Photogrammetria* 26: 51-75.

Weibel, R. and J.S. De Lotto 1988. Automated terrain classification for GIS modelling. *Proceedings of GIS/LIS'88*. ASPRS/ACSM, Falls Church, Virginia, 1988, 2: 618-627.

Weibel, R. 1989. *Concepts and Experiments for the Automation of Terrain Generalization*. Ph.D. Dissertation (in German), Geoprocessing Series 15, Zurich, Department of Geography, University of Zurich.

Weibel, R. and M. Heller 1990. A framework of digital terrain modelling. *Proceedings of the 4th International Symposium on Spatial Data Handling*, International Geographical Union, Columbus, Ohio: 219-229.

Weibel, R. and M. Heller 1991. Digital terrain modelling. In D.J. Maguire, M.F. Goodchild, D.W. Rhind (eds), *Geographical Information Systems: Principles and Applications*. Wiley & Sons: 269-297.

Westerveld, W.G., G.B.M. Pedroli, M. van den Broek, and J.M. Spoek 1984. Classification in landscape ecology: an experimental study. *Catena* 11: 51-63.

Weszka, J.S., C.R. Dyer, and A. Rosenfeld 1976. A comparative study of texture measures for terrain classification. *IEEE Transactions on Systems, Man and Cybernetics* SMC-6 (4): 269-285.

Wharton, S.W. 1982. A context-based land-use classification algorithm for high-resolution remotely sensed data. *Journal of Applied Photographic Engineering* 8 (1): 46-50.

Whittow, J. 1984. *Dictionary of Physical Geography*. Penguin, Middlesex.

Wiken, E.B. and G. Ironside 1977. The development of ecological land classification in Canada. *Landscape Planning* 4: 273-275.

Wiken, E.B. 1980. Rational and methods of ecological land surveys: an overview of Canadian approaches. *Ecological Land Classification Series* 11: 11-19.

Wood, W.F. and J.B. Snell 1960. *A Quantitative System for Classifying Landforms*. Technical Report EP-184, Quartermaster Research and Engineering Command, U.S. Army.

Wright, R.L. 1972. Principles in a geomorphological approach to land classification. *Zeitschrift fur Geomorphologie* N.F. 16 (4): 351-373.

Young, A. 1971. *Slope Profile Analysis, the System of best Units, Slopes, Form and Process*. Institute of British Geographers Special Publication No.3.

Young, A. 1972. *Slopes*. Oliver and Boyd, Edinburgh.

Young, M. 1978. *Terrain Analysis: Program Documentation*. Report on Grant DA-ERO-591-73-60040 Statistical Characterization of Altitude Matrices by Computer, European Research Office, U.S. Army, I.S. Evans, Principal Investigator, University of Durham, England.

Zevenbergen, L.W. and C.R. Thorne 1987. Quantitative analysis of landsurface topography. *Earth Surface Processes and Landforms* 12: 47-56.

Zusne, L. 1970. *Visual Perception of Form*. Academic Press, London.

Appendix 1

Relevant Definitions of Landform Categories and Classification Schemes

Table A1.1. Comparison of Surface Expression Definitions between Canadian System of Soil Classification (E.S.C.C., 1987a) and Terrain Classification System (Howes & Kenk, 1988)

Terrain Classification	Soil Classification
plain - level or very gently sloping, unidirectional surface; local surface irregularities generally have a relief of less than 1 metre. Slopes < = 5% (3)	**level** - A flat or very gently sloping, unidirectional surface with a generally constant slope not broken by marked elevations and depressions. Slopes generally < 2% (1)
gentle slope - unidirectional surface with a slope gradient 3-15 (5-26%), and a smooth, longitudinal profile that is either straight, concave or convex; local surface irregularities generally have a relief < 1m.	**inclined** - sloping, unidirectional surface with a generally constant slope not broken by marked irregularities; slopes 2-70% (1-35); form of inclined slopes is not related to the initial mode of origin of the underlying material.
moderate slope - same as above slope gradient 15-26 (26-50%)	
moderately steep slope - same as above; slope gradient 26-35 (50-70%).	
steep slopes - same as above: slope gradients > 35 (70%)	**steep** - Erosional slopes > 70% (35), on both consolidated and unconsolidated materials. The form of a steep erosional slope on unconsolidated materials is not related to the initial mode of origin of the underlying material.
rolling - Elongated hillocks with slopes dominantly between 3 and 15 (5-26%) with local relief > 1m. In plan, assemblage of parallel or sub-parallel linear forms with subdued relief.	**rolling** - very regular sequence of moderate slopes extending from rounded sometimes confined concave depressions to broad, rounded convexities producing a wavelike pattern of moderate relief. Slope length is often 1.6 km or greater and gradients > 5% (3).
ridges - Elongated hillocks with slopes dominantly between 15 and 35 (26-70%) if composed of unconsolidated materials; bedrock slopes may be steeper. Local relief >1m. In plan, an assemblage of parallel or subparallel linear forms.	**ridged** - long, narrow elevation of the surface, usually sharp crested with steep sides. The ridges may be parallel to subparallel, or intersecting.

undulating - gently sloping hillocks and hollows with multidirectional slopes generally up to 15 (26%); local relief > 1m. In plan, assemblage of non-linear, generally chaotic forms that are rounded or irregular in cross-profile.	**undulating** - very regular sequence of gentle slopes that extends from rounded, sometimes confined concavities to broad rounded convexities producing a wavelike pattern of low local relief. Slope length generally < 0.8 km and the dominant slope gradient is 2-5% (1-3).
hummocks - steep sided hillocks and hollows with multidirectional slopes dominantly between 15 and 35 (26-70%) if composed of unconsolidated materials; bedrock slopes may be steeper. Local relief >1m. In plan, assemblage of non-linear,generally chaotic forms that are rounded or irregular in cross-profile.	**hummocky** - very complex sequence of slopes extending from somewhat rounded depressions or kettles of various sizes to irregular to conical knolls and knobs Generally lack of concordance between knolls and depressions. Slopes generally 9-70 % (5-35)
depressions - Circular or irregular area of lower elevation than the surrounding terrain and marked by an abrupt break in slope; side slopes within the depression are steeper than the surrounding terrain; depressions are two or more meters in depth.	
terrace - a single or assemblage of step-like forms where each step-like form consists of a scarp face and a horizontal or gently inclined surface above it.	**terraced** - scarp face and the horizontal or gently inclined surface above it.
fan - relatively smooth segment of a cone with a slope gradient from apex to toe, up to, and incl. 15 (26%); longitudinal profile that is either straight, concave or convex.	**fan** - fan shaped form similar to segment of a cone and having a perceptible gradient from the apex to the toe.
cone - cone or segment of a cone with a relatively smooth slope gradient from apex to toe > 15 (26%), and a longitudinal profile that is either straight, concave or convex.	**apron** - relatively gentle slope at the foot of a steeper slope formed by materials from the steeper, upper slopes

veneer - mantle of unconsolidated materials too thin to mask the minor irregularities of the surface of the underlying material. It ranges in thickness form 10 cm to 1 meter and possesses no form typical of the material genesis.

blanket - mantle of unconsolidated materials thick enough to mask minor irregularities of the surface of the underlying units, but still conforms to the general underlying topography. Blanket > 1m thick; outcrops of the underlying unit are rare.

Table A1.2. Comparison of Slope Classifications between Canadian System of Soil Classification (E.C.S.S., 1987a) and Terrain Classification System (Howes & Kenk, 1988)

Terrain Classification			Soil Classification		
0-3	0-5%	plain	0	0-0.5%	level
			0.3-1.5	0.5-2.5%	nearly level
			1-3	2-5%	very gentle
>3-15	5-26%	gentle slope	3.5-5	6-9%	gentle slopes
			6-8.5	10-15%	moderate slopes
			9-17	16-30%	strong slopes
>15-26	26-50%	moderate slope	17-24	31-45%	very strong
>26-35	50-70%	moderately steep	25-35	46-70%	extreme slopes
>35	>70%	steep slope	35-45	70-100%	steep slope
			>45	>100%	very steep

Table A1.3. Comparison of Surface Expression Definitions Used in the Sand River Surficial Geology Survey (Andriashek & Fenton, 1989) and the County of St.Paul Soil Survey (Brierley *et al.*, 1990)

Surficial Geology Survey	**Soil Survey**
flat - local relief < 1 m.	**level** - flat or very gently sloping, unidirectional surface with a generally constant slope not broken by marked elevation and depression. Slope < 2 %
varied - hummocky, rolling, and flat terrain, relief qlocally high	**dissected** - long unidirectional slopes which contain gullies or dissections. The slope length within these landscape > 300 m.
terrace	**terraced** - surface form consisting of a riser and the horizontal or gently inclined surface (tread) above it. The presence of the riser limits access within the map
rolling - alternating concave and convex morphologic elements with a length to width ratio of more than 2; elements parallel to nonoriented	**undulating** - wave-like pattern of very gentle slopes with low local relief. Slope length is generally < 0.5 km and slope gradients 2-5%
ridged - one or more convex parallel to sub-parallel, morphologic elements with a length to width ratio of more than 2; may rest on a level surface or have associated hollows	**ridged** - long narrow elevation of the surface usually sharp crested with steep sides. Ridges may be parallel, subparallel or intersecting
hummocky - assemblages of hills and hollows; approximately equidimensional	**hummocky** - a very complex sequence of slopes extending from somewhat rounded depressions or kettles of various sizes to irregular to conical knolls or knobs. There is a general lack of concordance between knolls and depression. Slope 9-70 %
	inclined - sloping, unidirectional surface not broken by marked irregularities. slopes are 2-30% and > 300 m in length.

Table A1.4. Comparison of Morphometric Modifier Classifications Used in the Sand River Surficial Geology Survey (Andriashek & Fenton, 1989) and the County of St.Paul Soil Survey (Brierley *et al.*, 1990)

local relief classes used in geology survey		**slope classes** used in soil survey	
low	< 3m	level	0- 2%
		very gentle	2- 5%
moderate	3-10m	gentle	5- 9%
		moderate	9-15%
high	>10m	strong	15-30%

Table A1.5. Curvature Classification Scheme after Young (1972)

description	degrees/100m	% slope / 25 m
very concave	< -10	< -4.4
concave	-10 < -1	-4.40 < -0.44
straight	-1 < 1	-0.44 < 0.44
convex	1 < 10	0.44 < 4.44
very convex	> 10	> 4.44

Table A1.6. Colour Scheme Used in Soil, Surficial Geology, and Automated Landform Classifications

	Landform Categories		
Colour	Soil Survey	Surficial Geology	Automated Classification
blue	lakes	lakes	
cyan	level(0-2%)	flat	level
green	undulating	rolling	undulating
yellow	hummocky-ridged	ridged, ridged-rolling hummocky-ridged	rolling
brown	hummocky	hummocky	hummocky-rolling, ridged, hummocky
grey		hummocky-rolling	
magenta	hummocky-inclined		
red	level(0-10%), dissected	varied, terraced	dissected

Appendix 2

Histograms and F-Test Results of Individual DTM Distributions

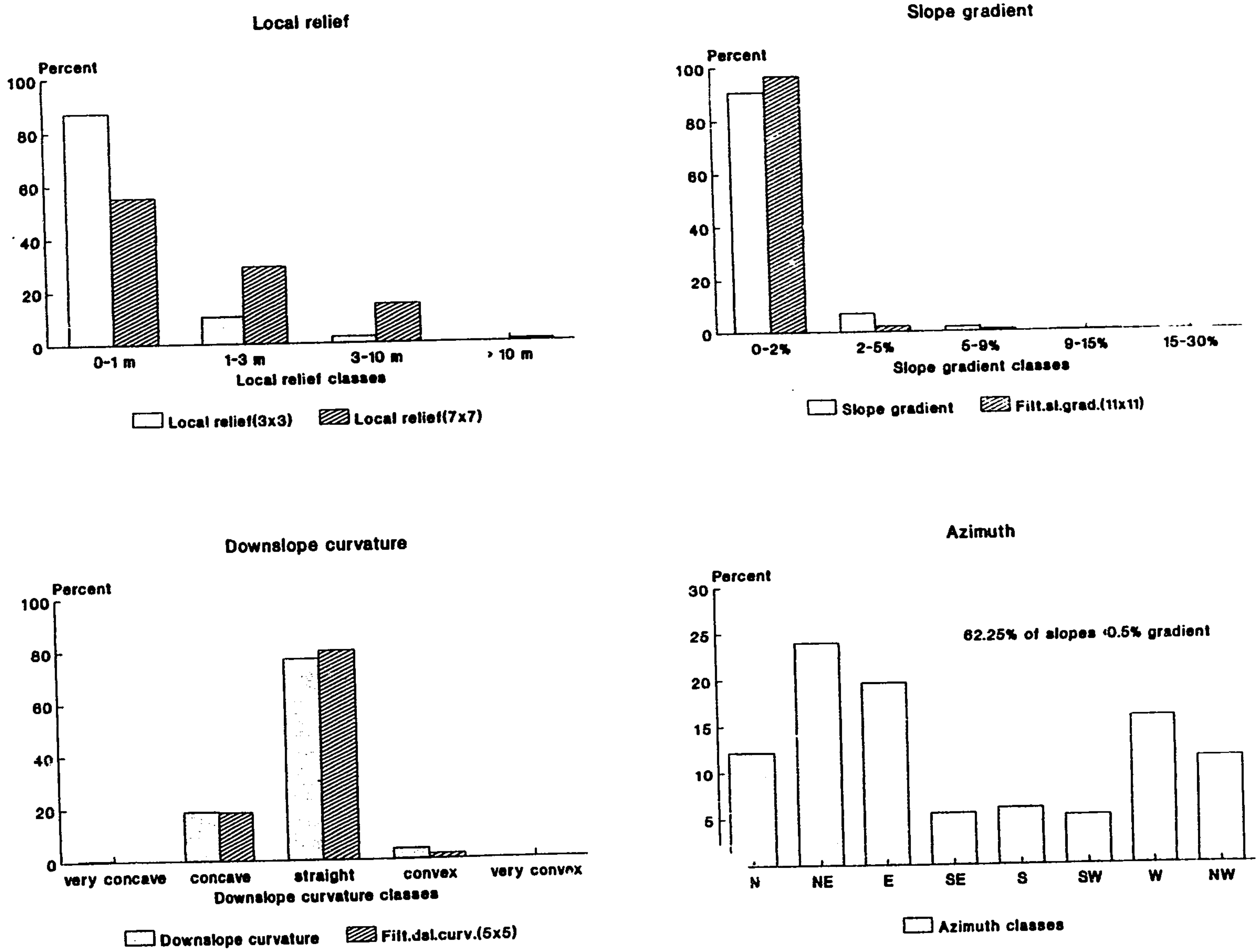


Figure A2.1.1. Classed frequency distribution of soil survey landform category *lake*

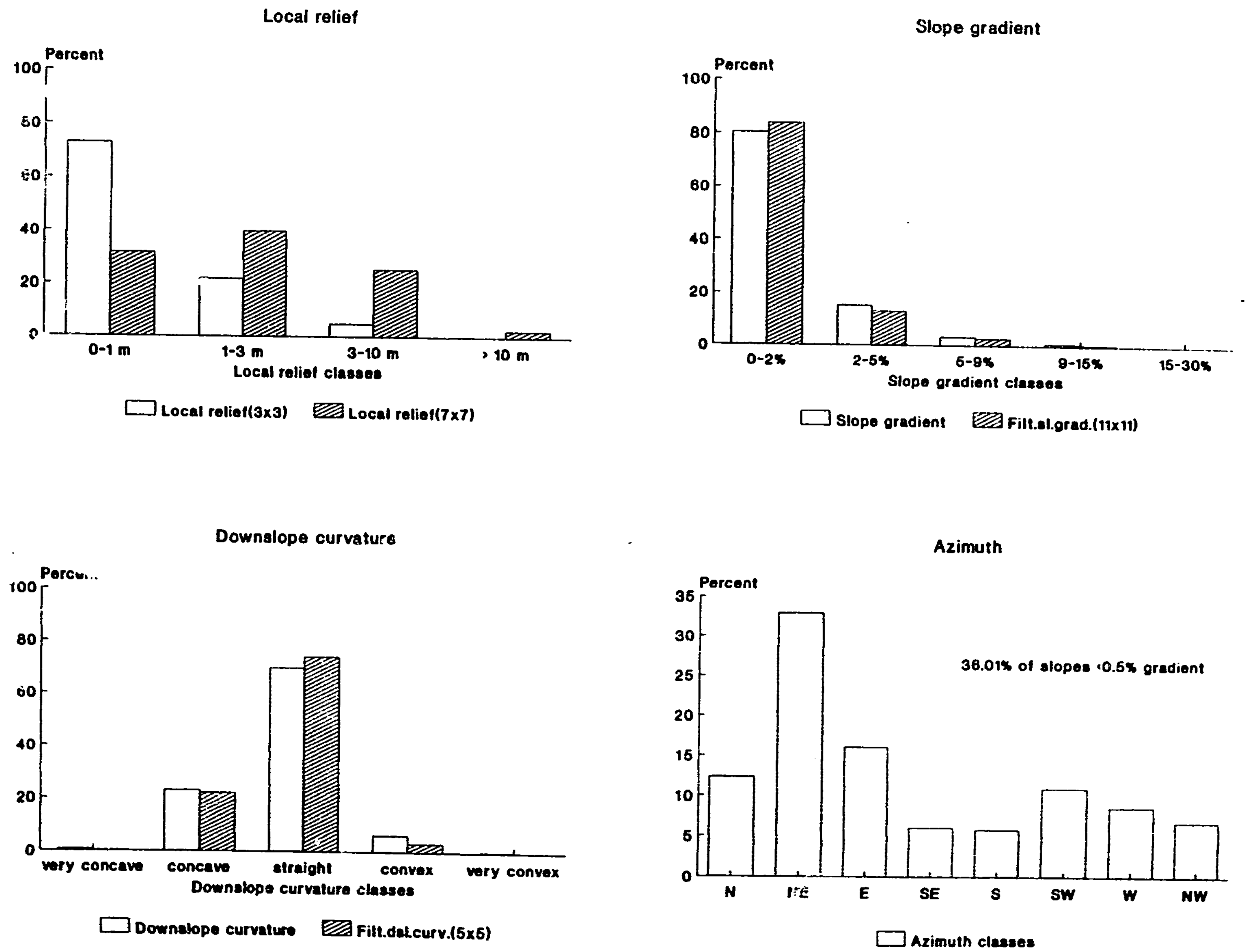


Figure A2.1.2. Classed frequency distribution of soil survey landform category *level(0-2%)*

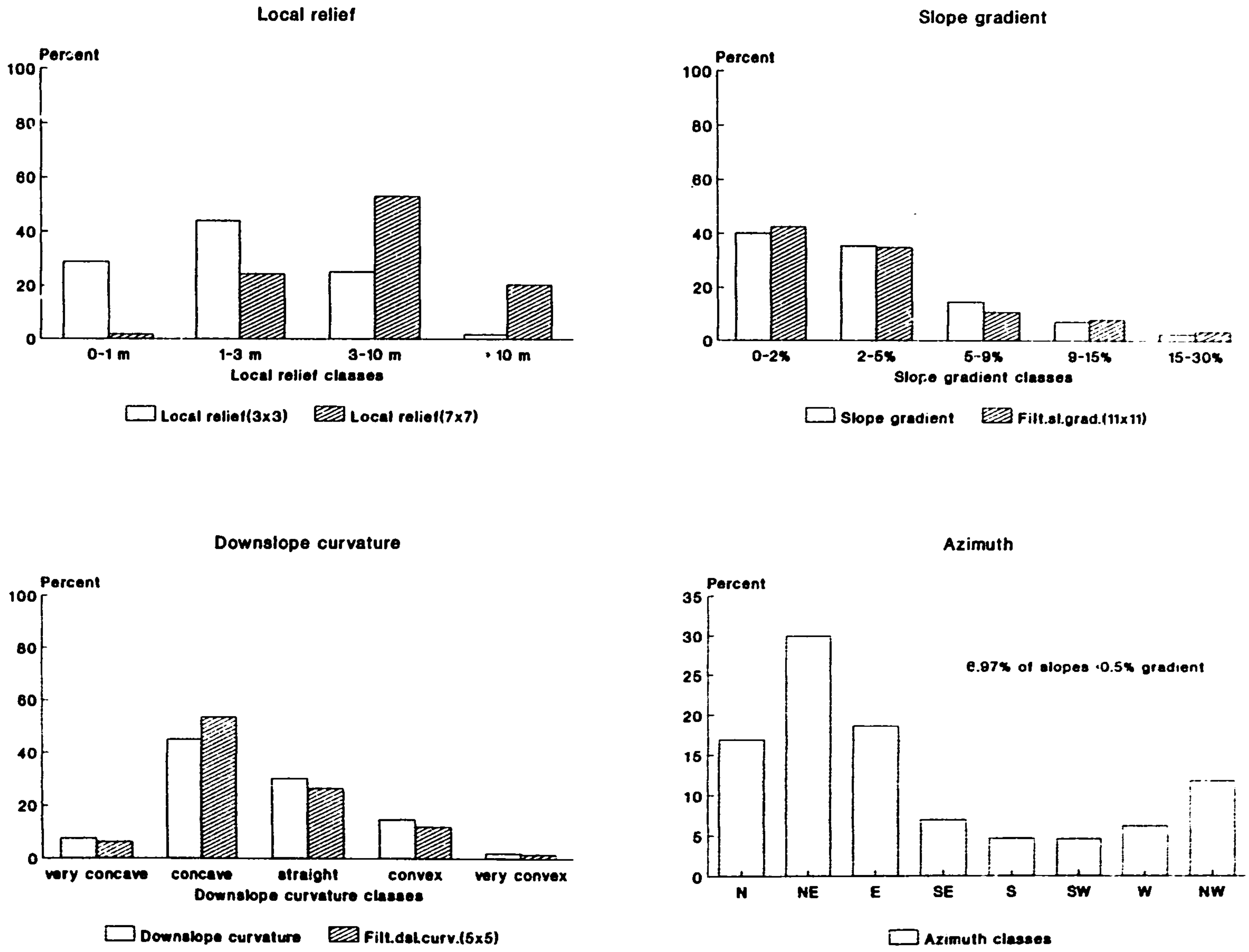


Figure A2.1.3. Classed frequency distribution of soil survey landform category *level(0-10%)*

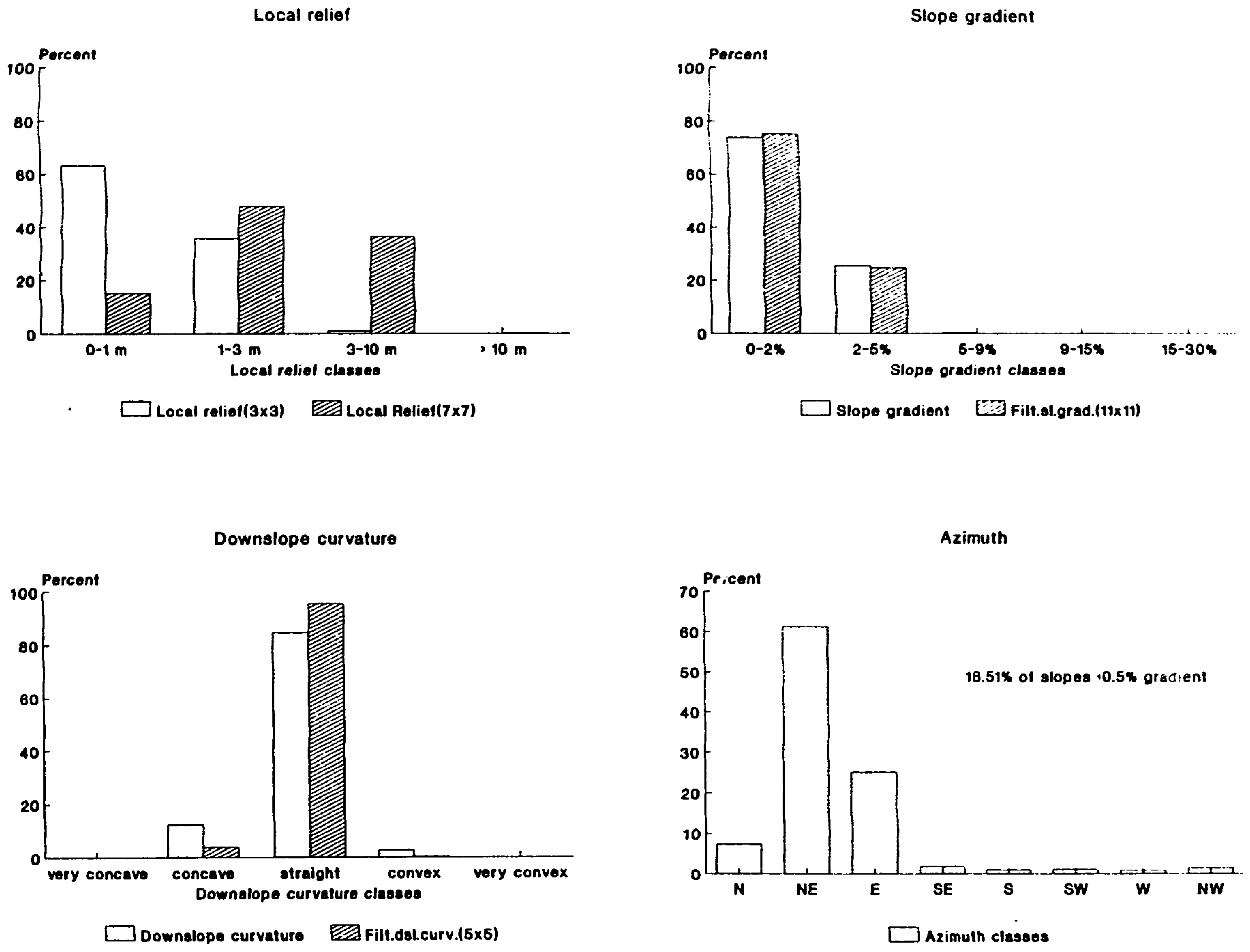


Figure A2.1.4. Classed frequency distribution of soil survey landform category *undulating(0-5%)*

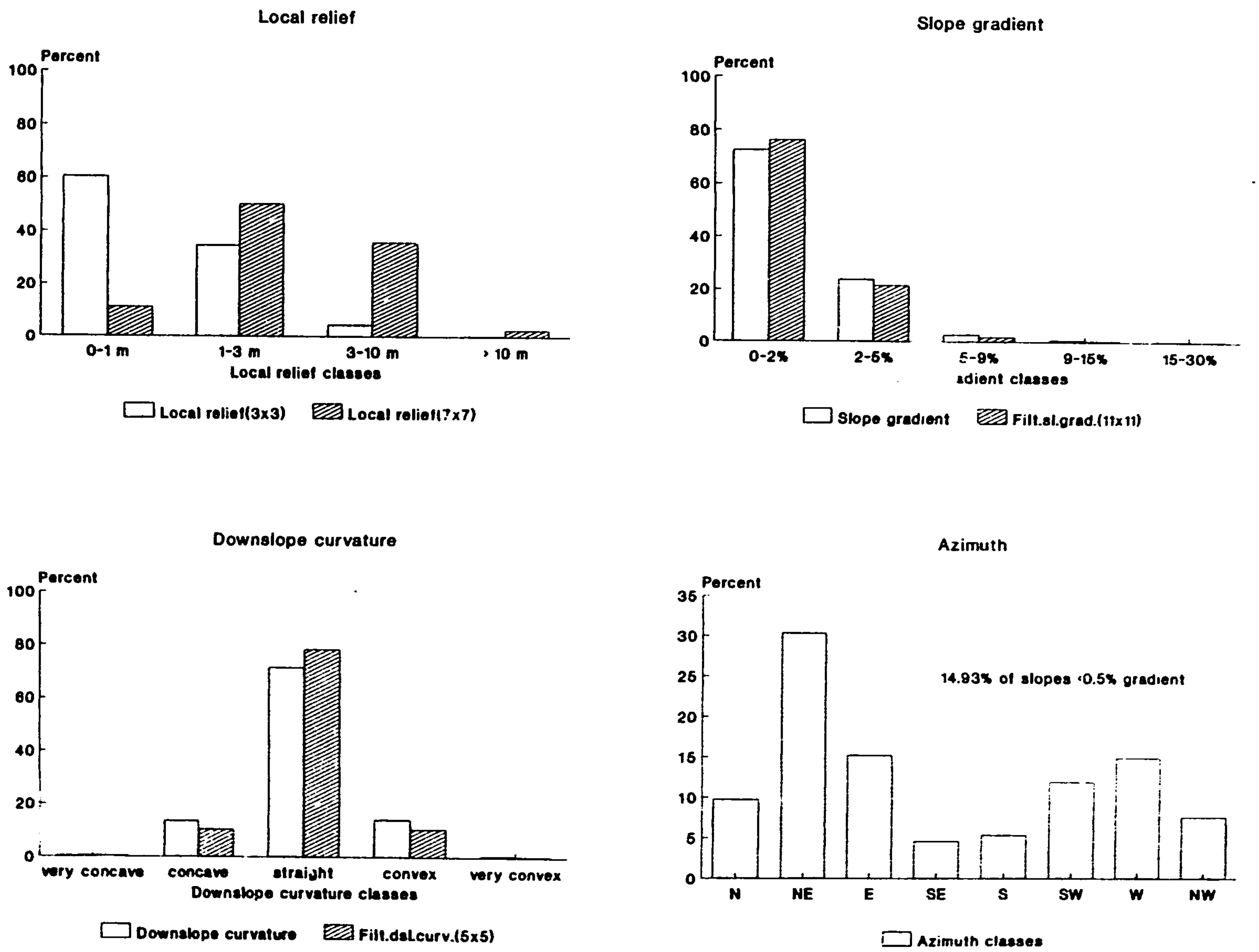


Figure A2.1.5. Classed frequency distribution of soil survey landform category *undulating(2-5%)*

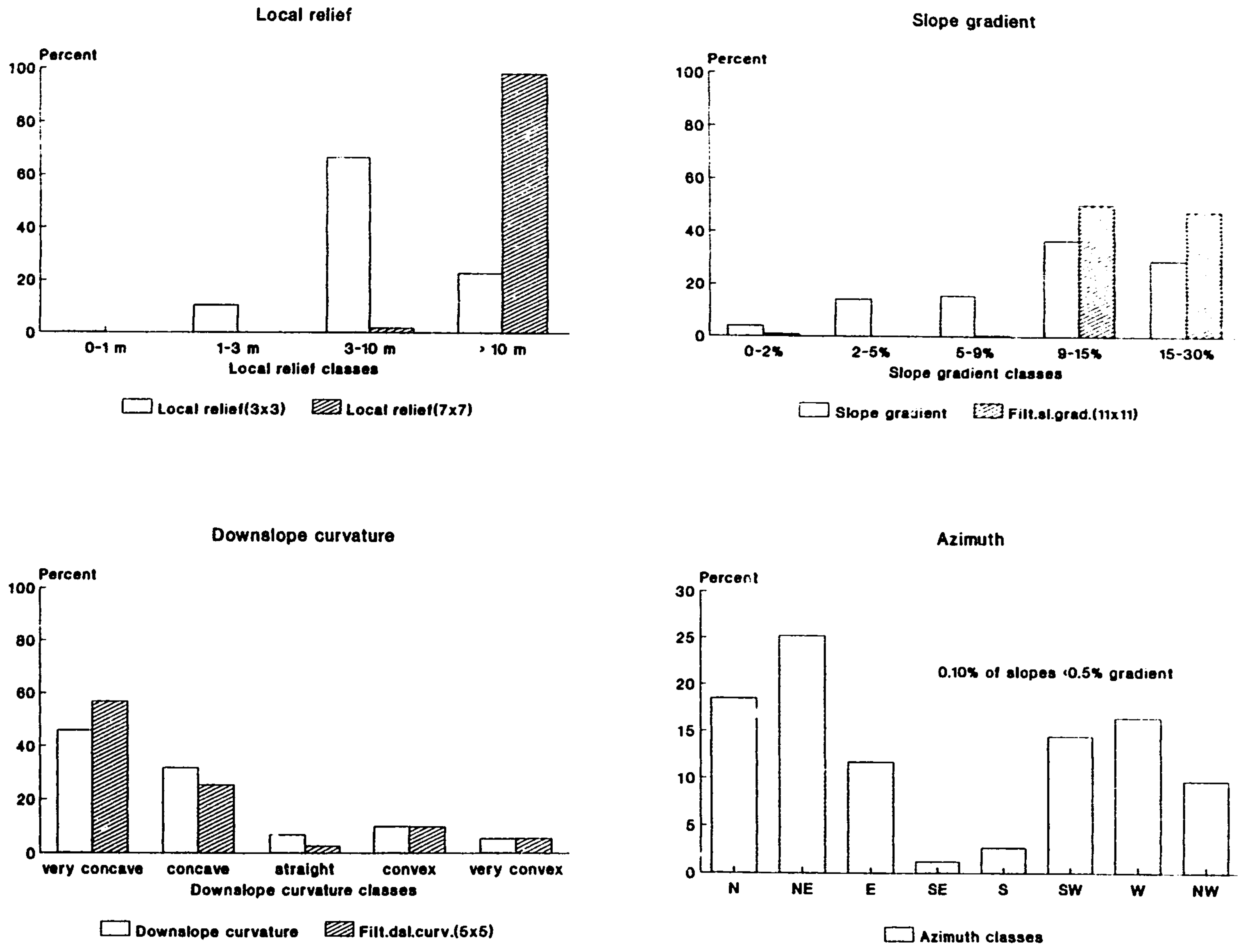


Figure A2.1.6. Classed frequency distribution of soil survey landform category *dissected(>5%)*

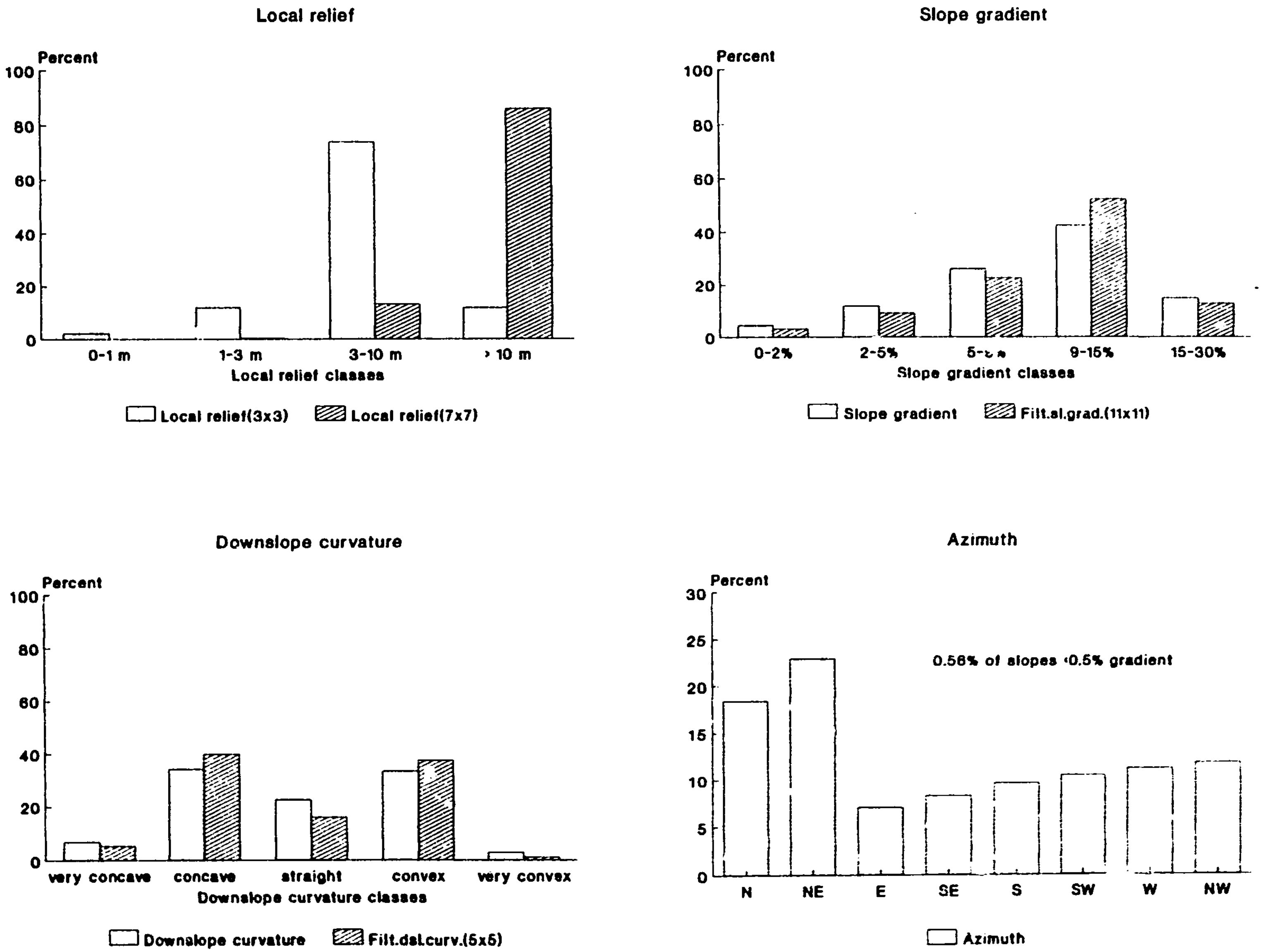


Figure A2.1.7. Classed frequency distribution of soil survey landform category *dissected(> 10%)*

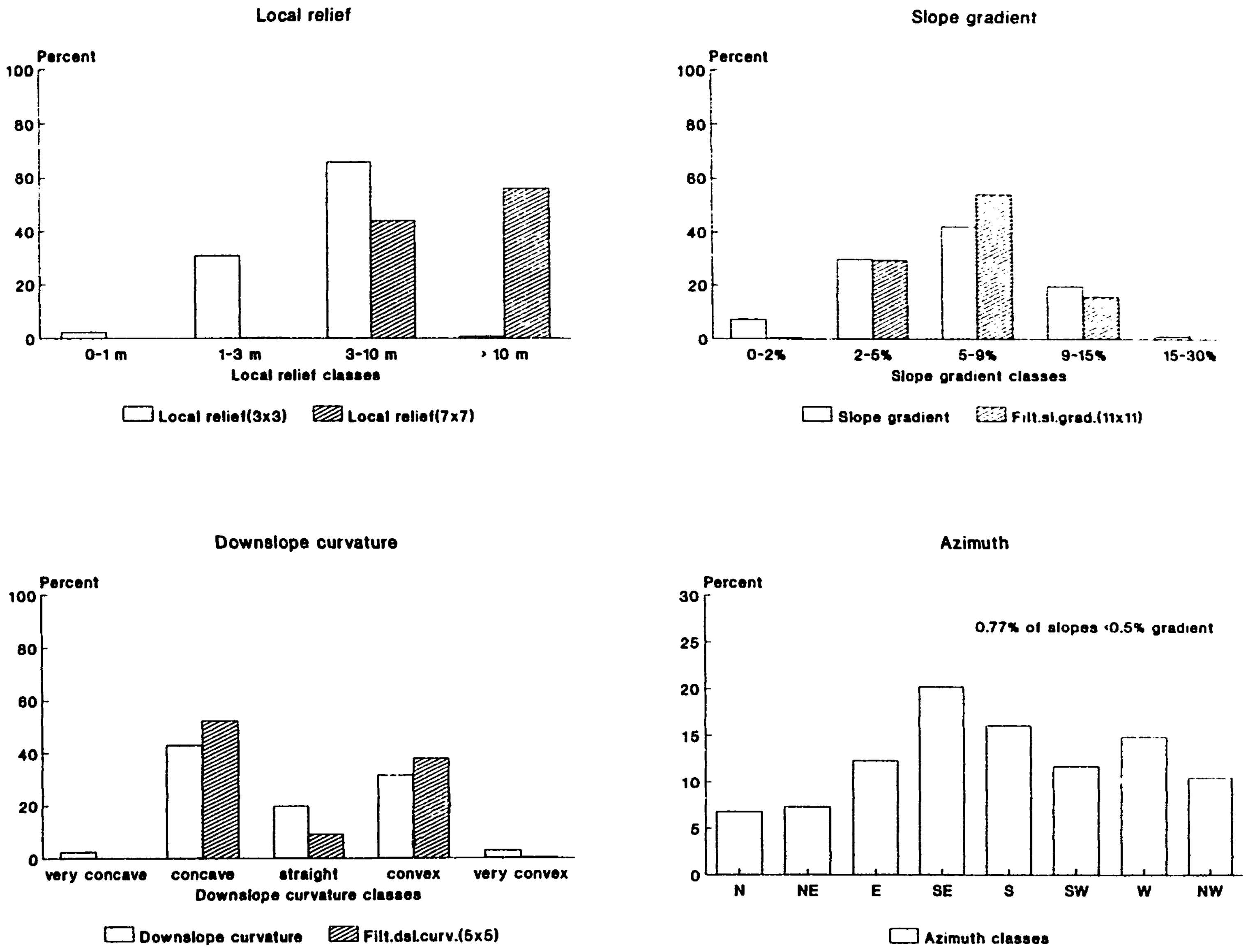


Figure A2.1.8. Classed frequency distribution of soil survey landform category *hummocky-inclined(>9%)*

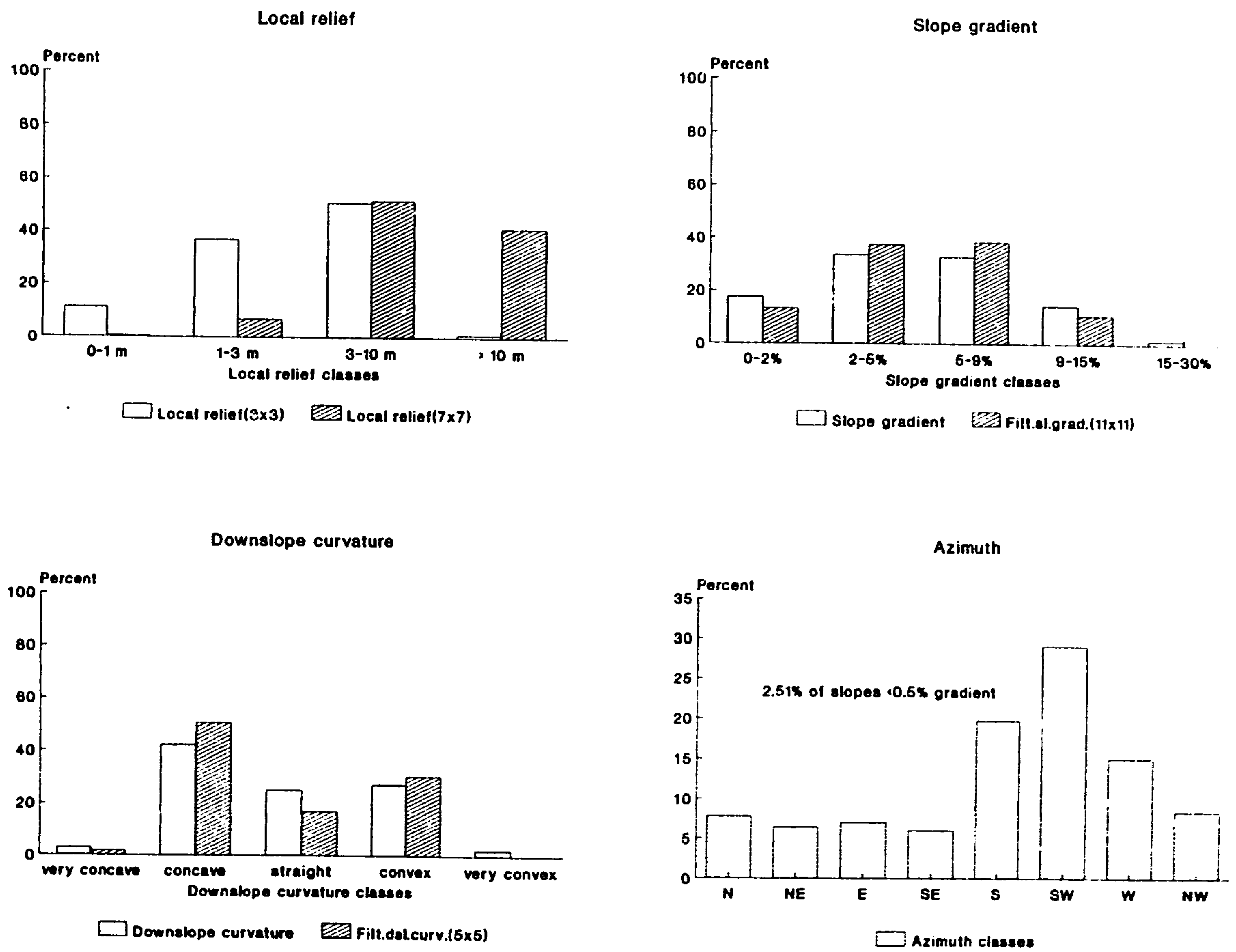


Figure A2.1.9. Classed frequency distribution of soil survey landform category *hummocky-inclined(>15%)*

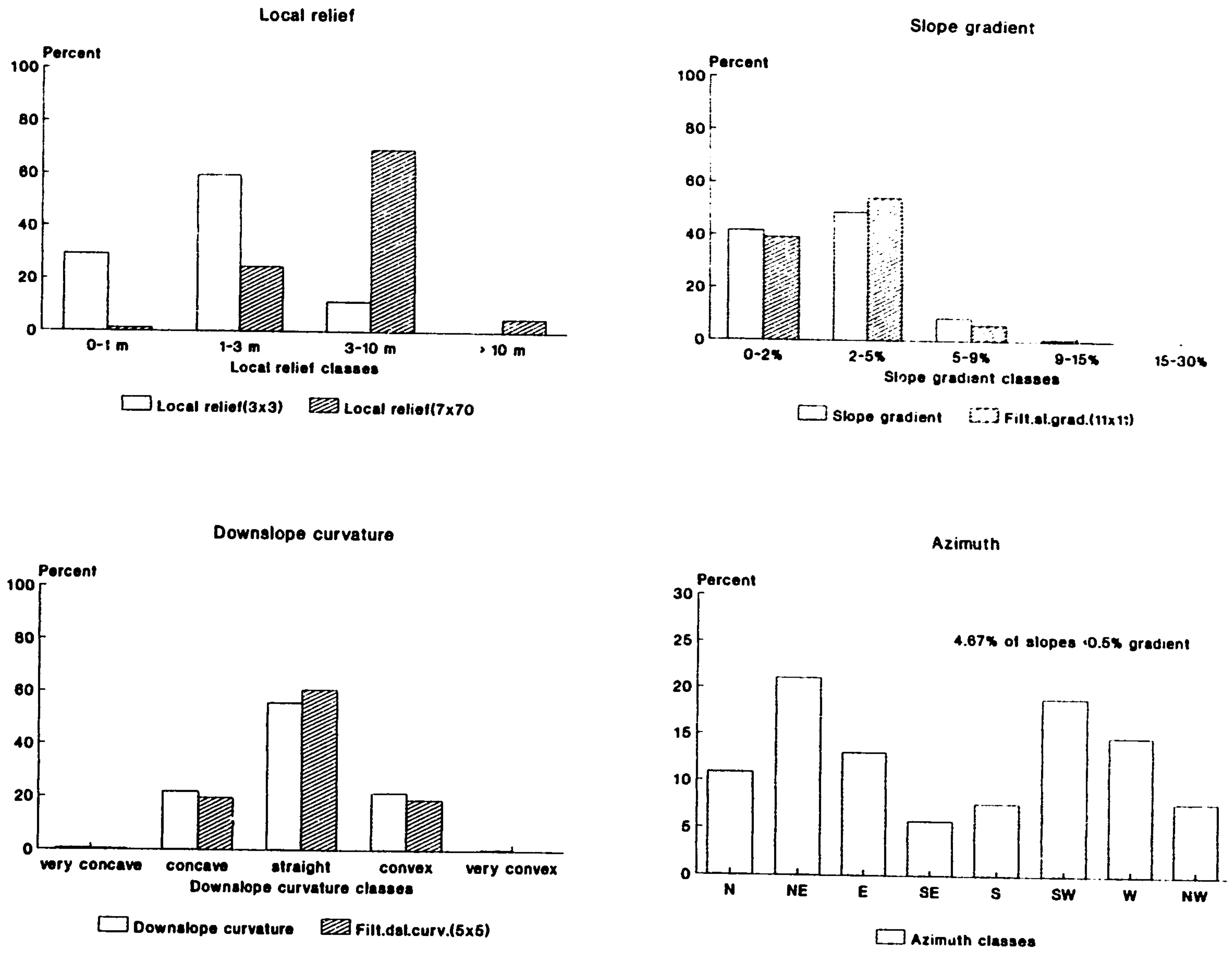


Figure A2.1.10. Classed frequency distribution of soil survey landform category *hummocky-ridged(5-9%)*

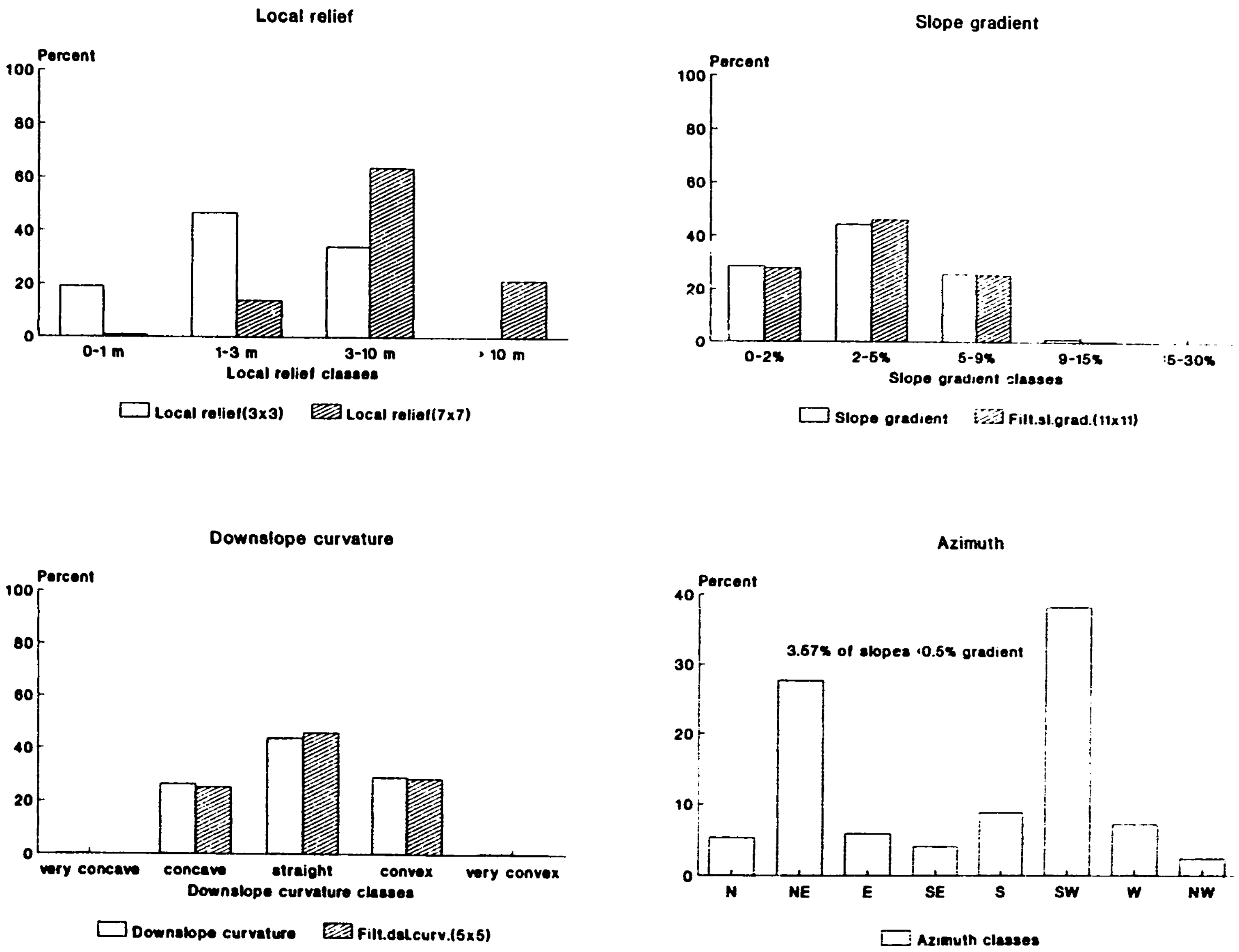


Figure A2.1.11. Classed frequency distribution of soil survey landform category *hummocky-ridged(9-15%)*

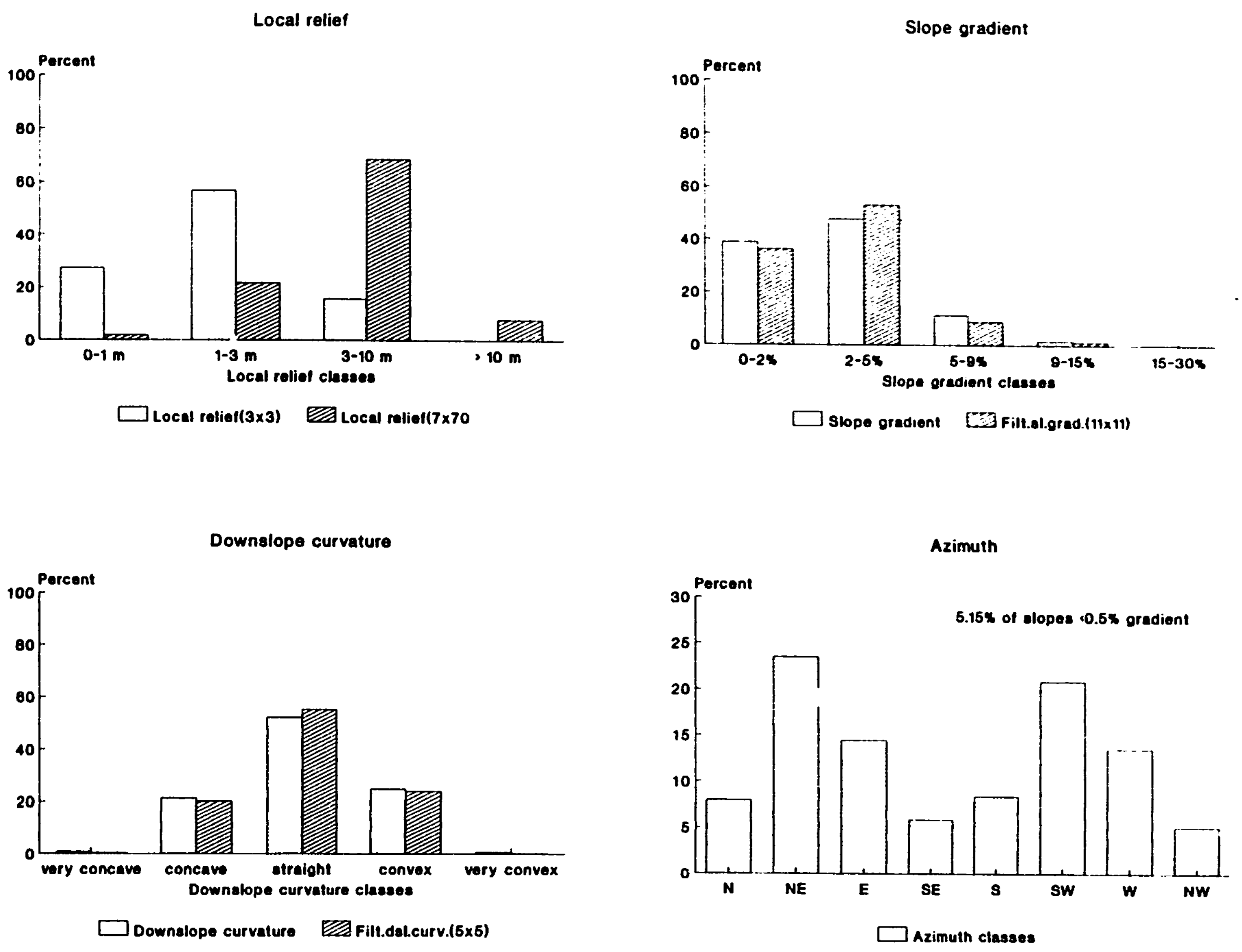


Figure A2.1.12. Classed frequency distribution of soil survey landform category *hummocky(5-9%)*

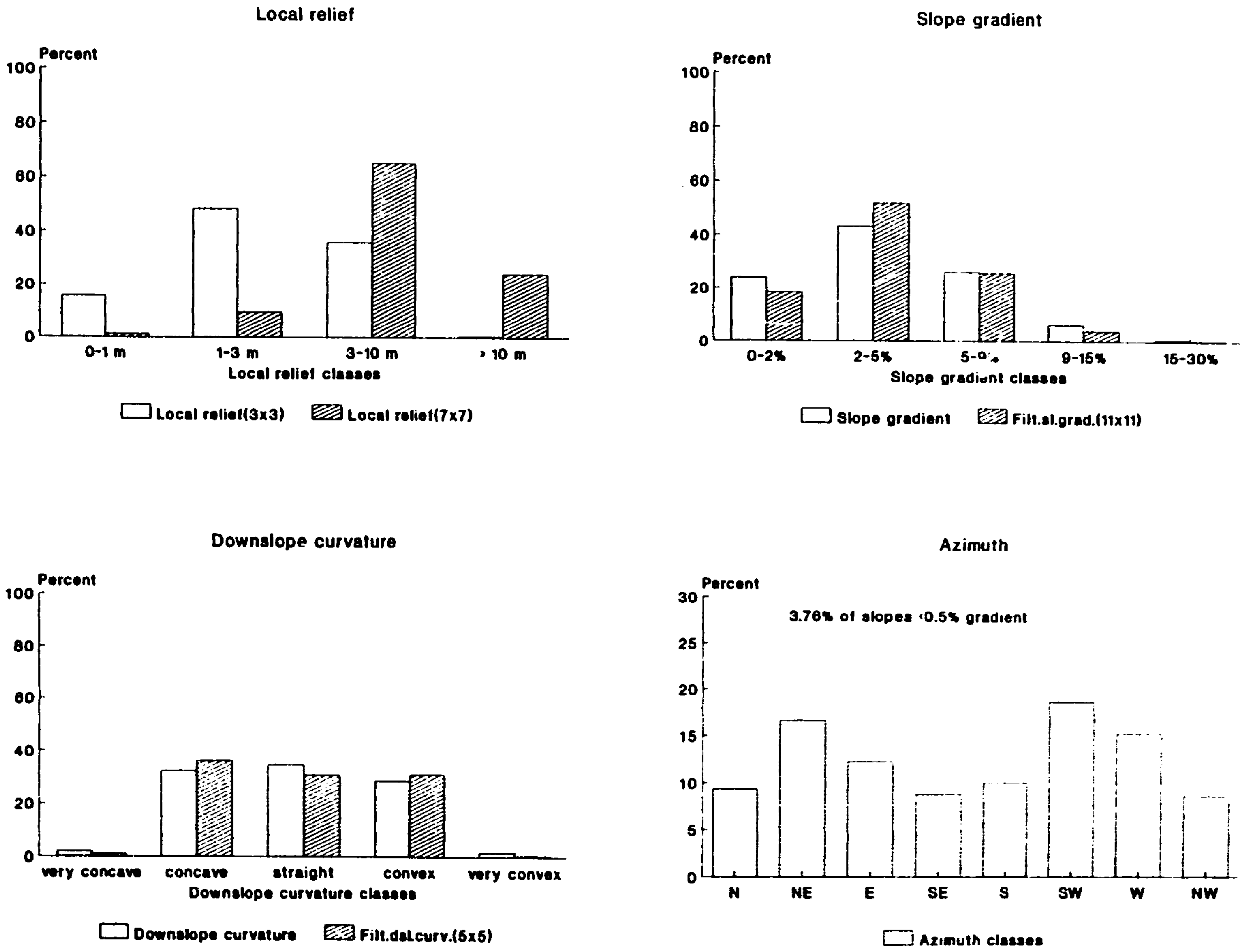


Figure A2.1.13. Classed frequency distribution of soil survey landform category *hummocky(9-15%)*

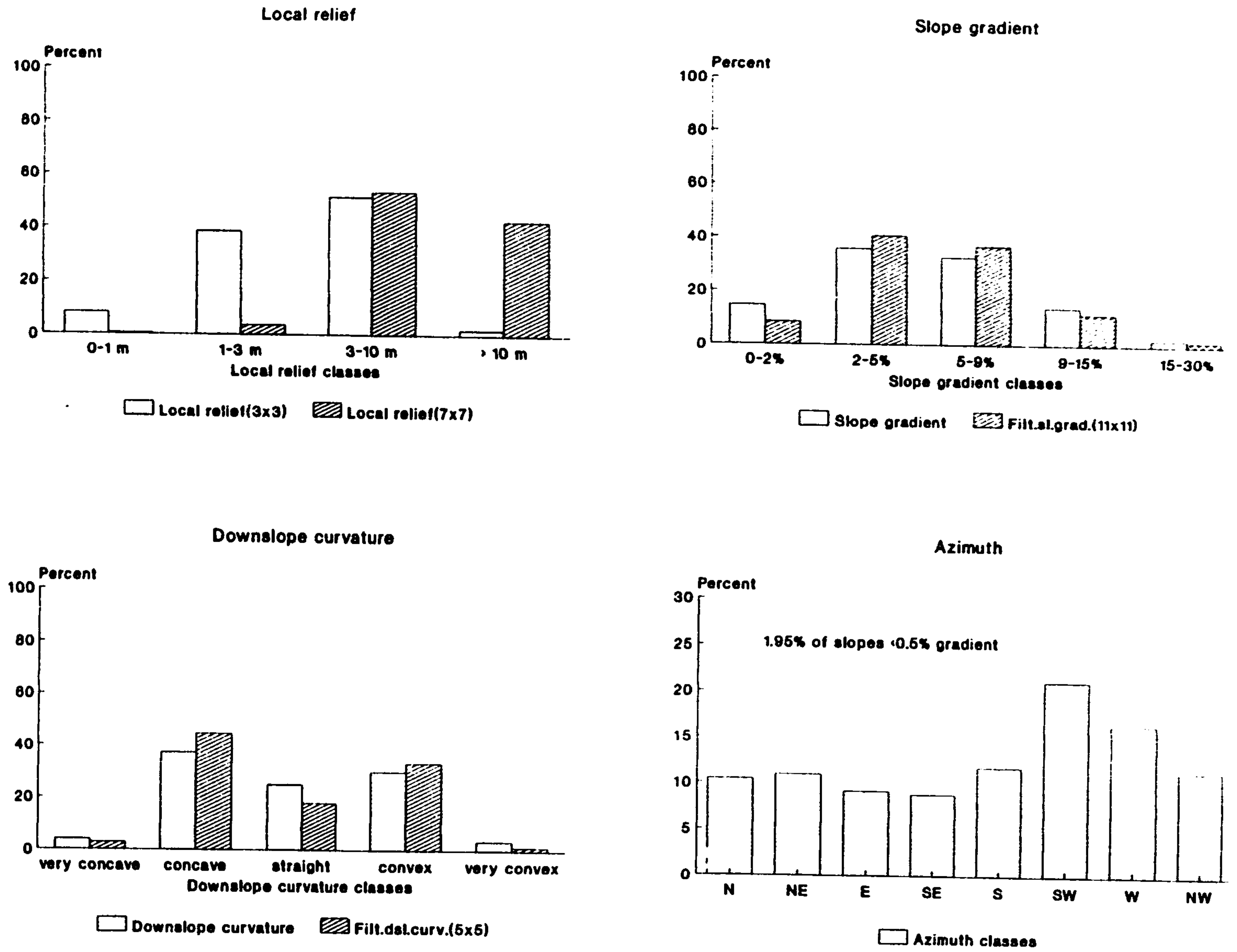


Figure A2.1.14. Classed frequency distribution of soil survey landform category *hummocky(15-30%)*

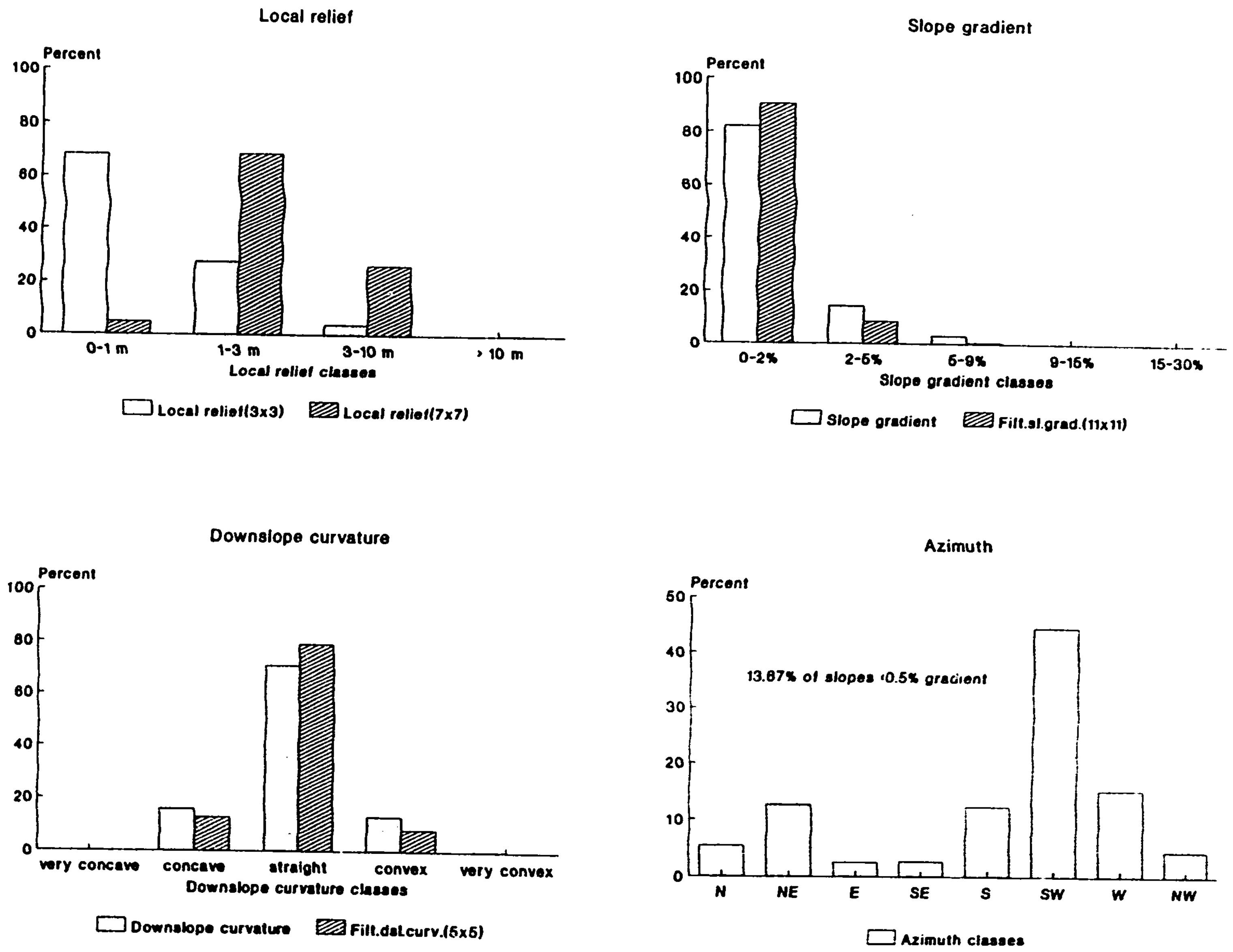


Figure A2.1.15. Classed frequency distribution of soil survey landform category *hummocky(5-15%)*

Legend for soil landform categories (Figures A2.2.1 to A2.2.3)

1 = lake, 2 = level(0-2%), 3 = level(0-10%), 4 = undulating(0-5%), 5 = undulating (2-5%),
6 = dissected(>5%), 7 = dissected(>10%), 8 = hum-inclined(>9%), 9 = hum=inclined(>15%),
10 = hum=ridged(5-9%), 11 = hum-ridged(9-15%), 12=hummocky(5-9%), 13 = hummocky(9-15%),
14 = hummocky(>15%), 15 = hummocky(5-15%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.00														
2	1.67	1.00													
3			1.00												
4	1.02			1.00											
5	1.66	1.01		1.69	1.00										
6			1.06			1.00									
7							1.00								
8			1.29			1.22		1.00							
9			1.17			1.10		1.11	1.00						
10	1.66	1.00		1.69	1.00					1.00					
11											1.00				
12		1.45			1.46					1.46	1.18	1.00			
13			1.52			1.44		1.18	1.30		1.47		1.00		
14			1.04			1.02		1.25	1.13				1.47	1.00	
15	1.25			1.23											1.00

Figure A2.2.1. Matrix of F-test results for local relief(7x7) distributions between soil landform categories at significance level < 1%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.00														
2		1.00													
3			1.00												
4	1.43			1.00											
5		1.03			1.00										
6						1.00									
7			1.59			1.69	1.00								
8			1.41					1.00							
9			1.19					1.19	1.00						
10		1.10			1.08					1.00					
11		1.59			1.55					1.44	1.00				
12		1.59			1.55					1.44	1.00	1.00			
13			1.58					1.12	1.33				1.00		
14			1.01				1.60	1.40	1.18				1.57	1.00	
15	1.05			1.50											1.00

Figure A2.2.2. Matrix of F-test results for slope gradient distributions between soil landform categories at significance level < 1%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.00														
2	1.38	1.00													
3			1.00												
4				1.00											
5		1.53			1.00										
6						1.00									
7			1.11				1.00								
8								1.00							
9								1.07	1.00						
10		1.62			1.06					1.00					
11		1.57			1.03					1.03	1.00				
12					1.25					1.18	1.21	1.00			
13								1.20	1.12				1.00		
14			1.34				1.21	1.50	1.61					1.00	
15	1.08	1.49													1.00

Figure A2.2.3. Matrix of F-test results for downslope curvature distribution between soil landform categories at significance level < 1%

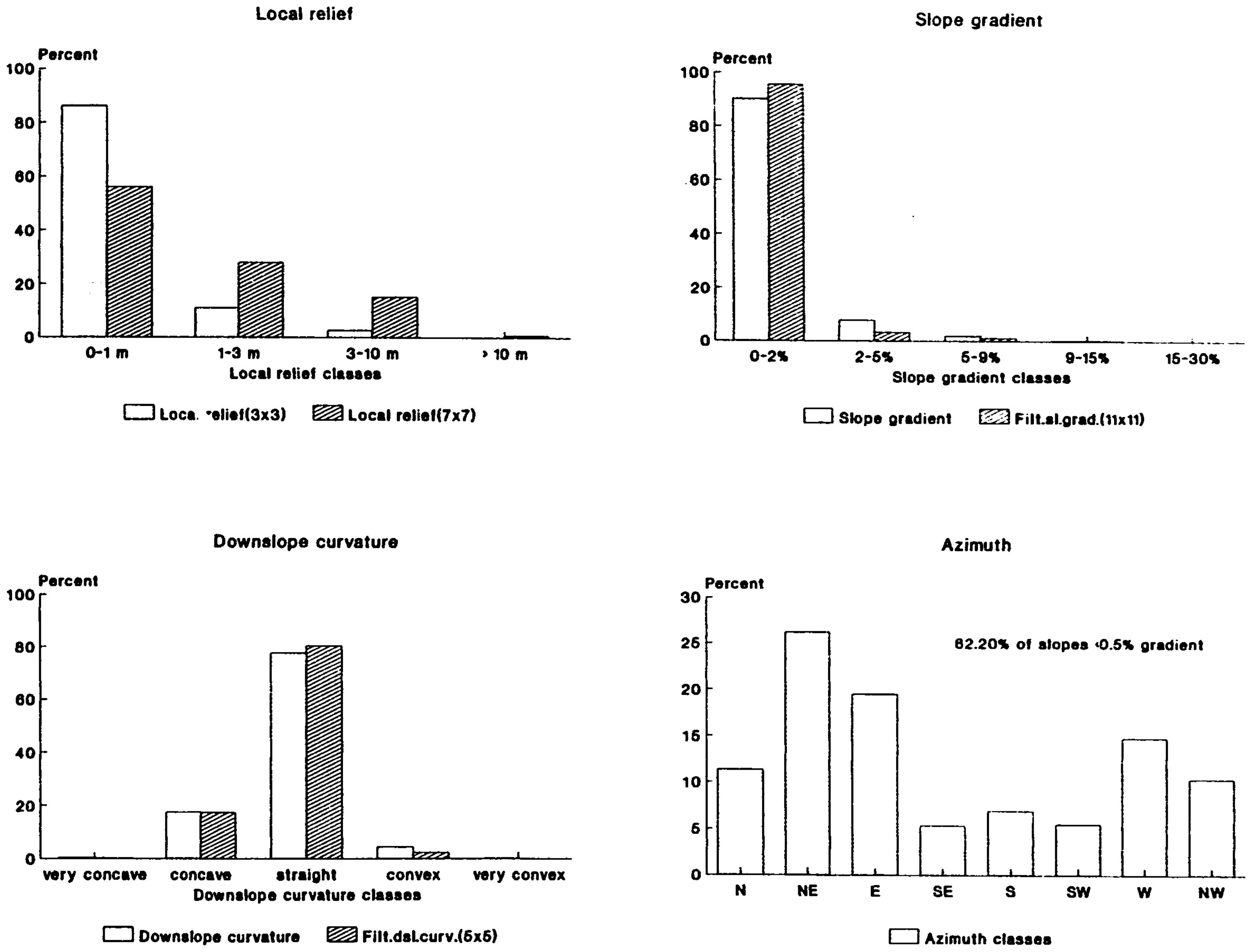


Figure A2.3.1. Classed frequency distribution of surficial geology landform category *lake*

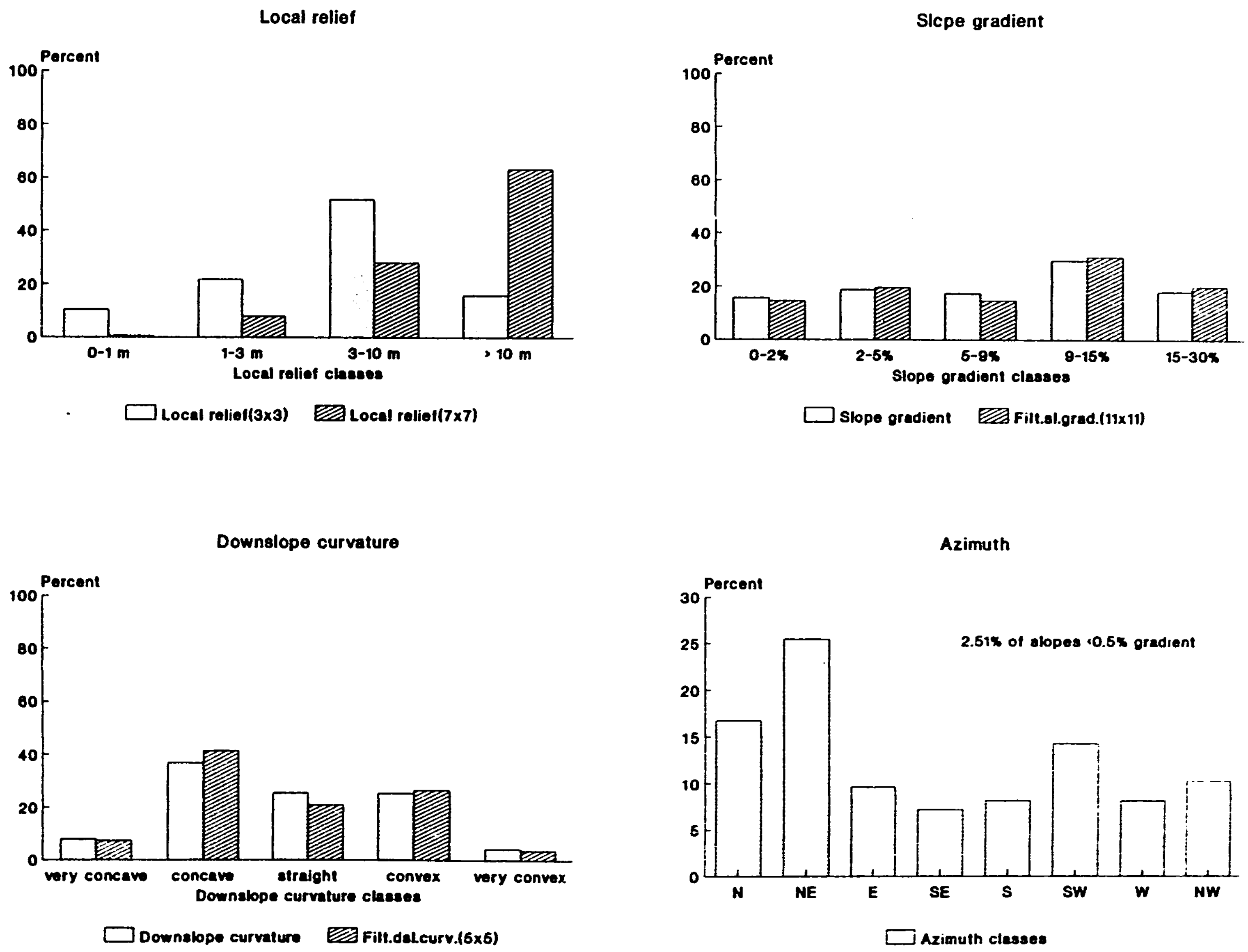


Figure A2.3.2. Classed frequency distribution of surficial geology landform category *varied*

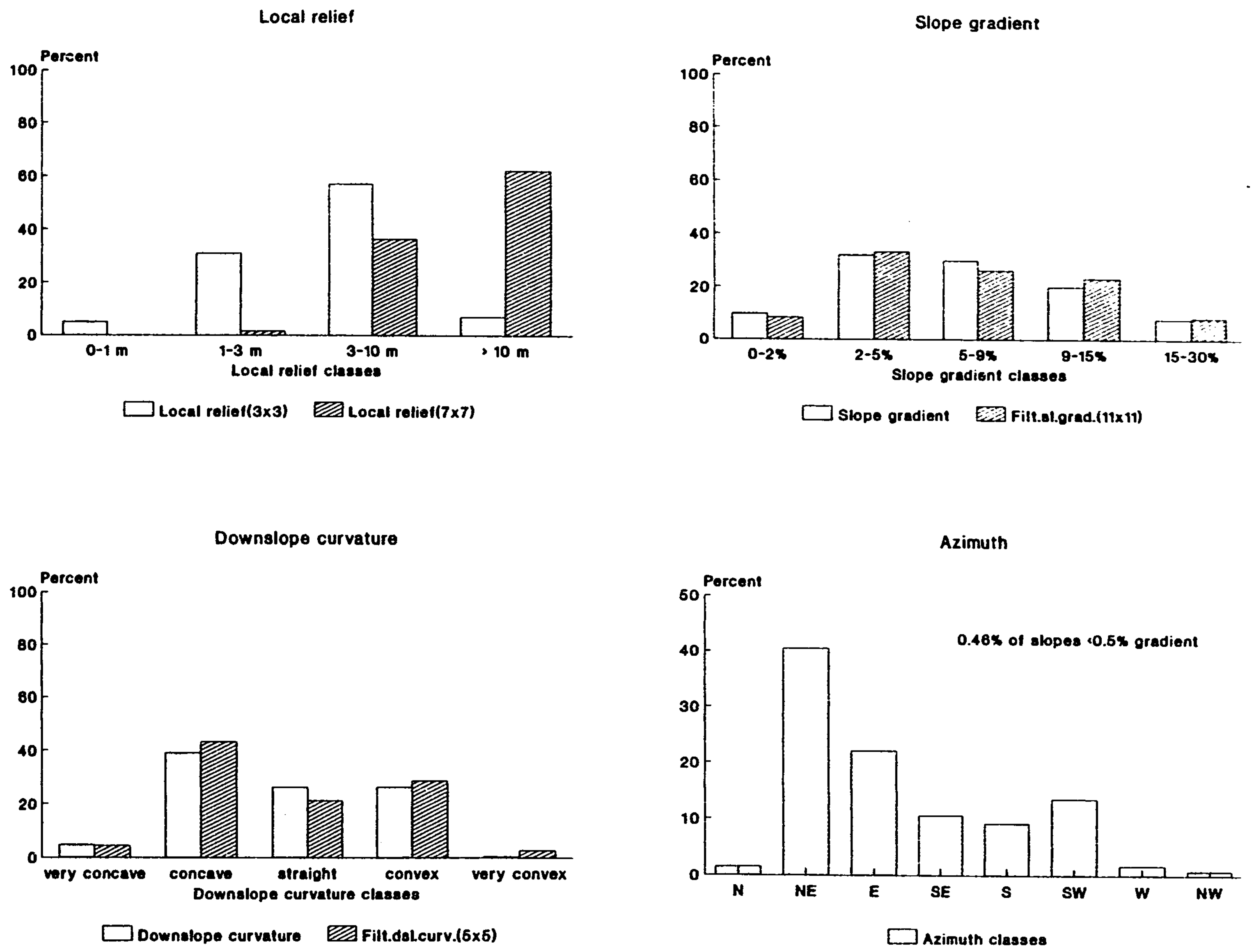


Figure A2.3.3. Classed frequency distribution of surficial geology landform category *terrace*

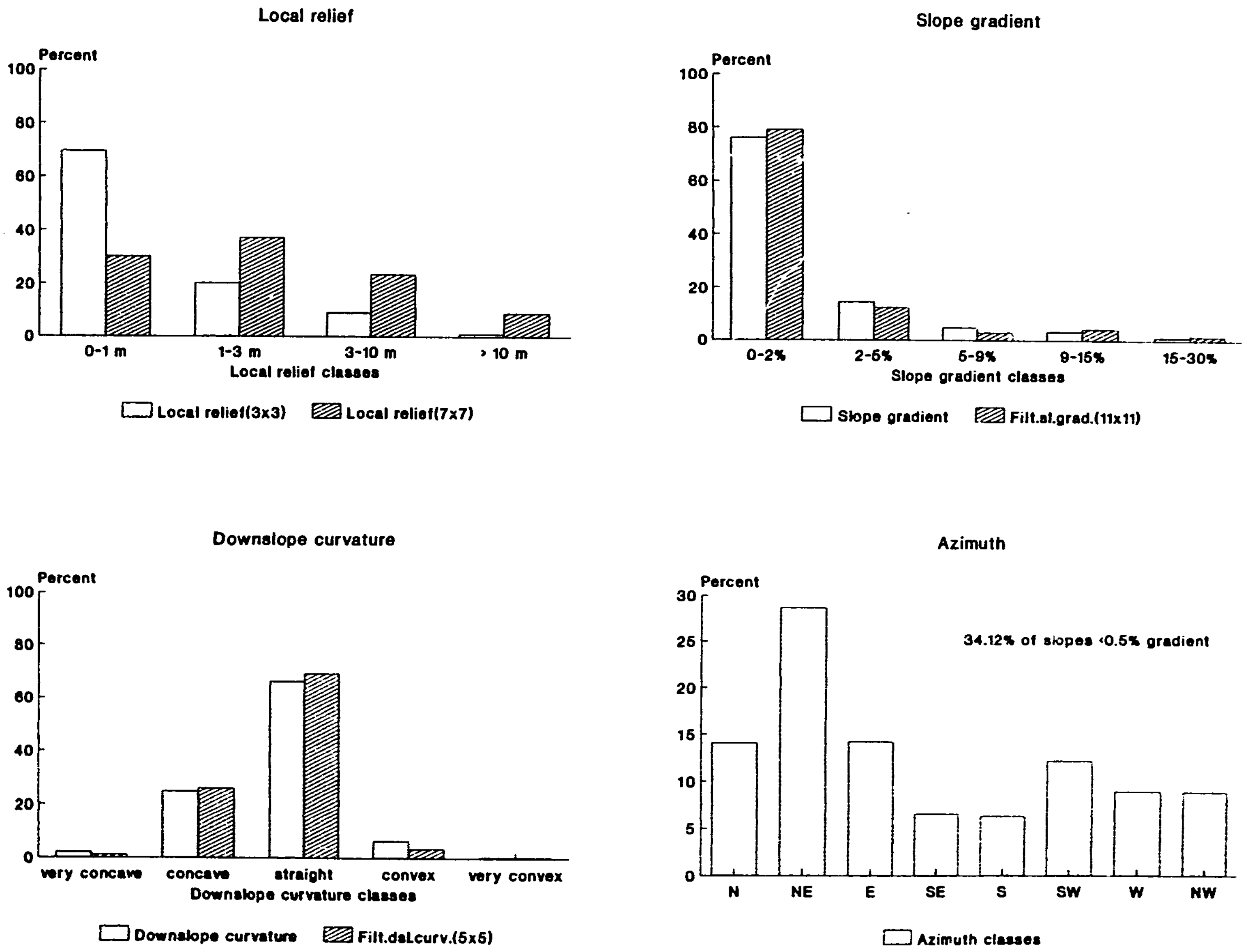


Figure A2.3.4. Classed frequency distribution of surficial geology landform category *flat*

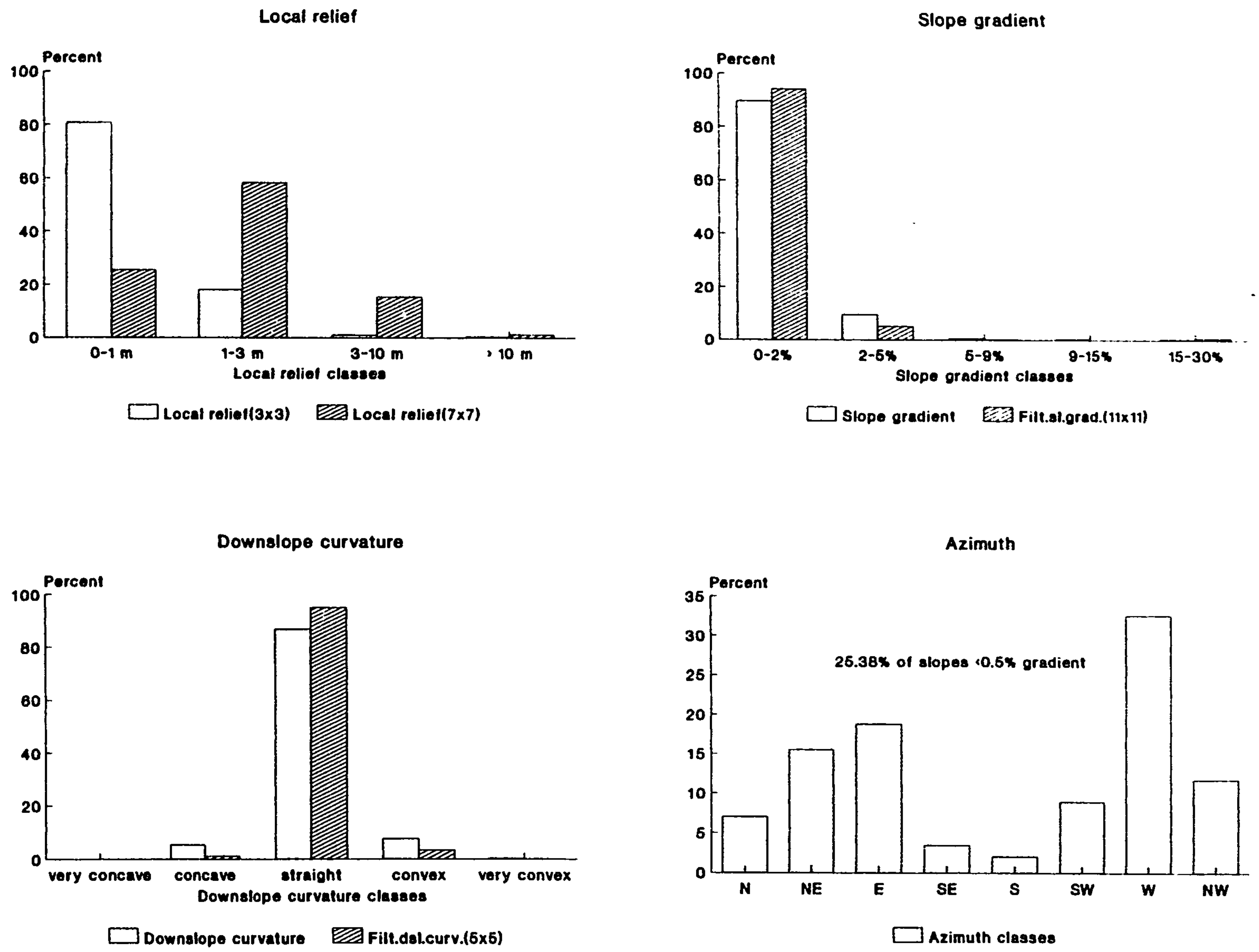


Figure A2.3.5. Classed frequency distribution of surficial geology landform category *flat-hummocky(0-3m)*

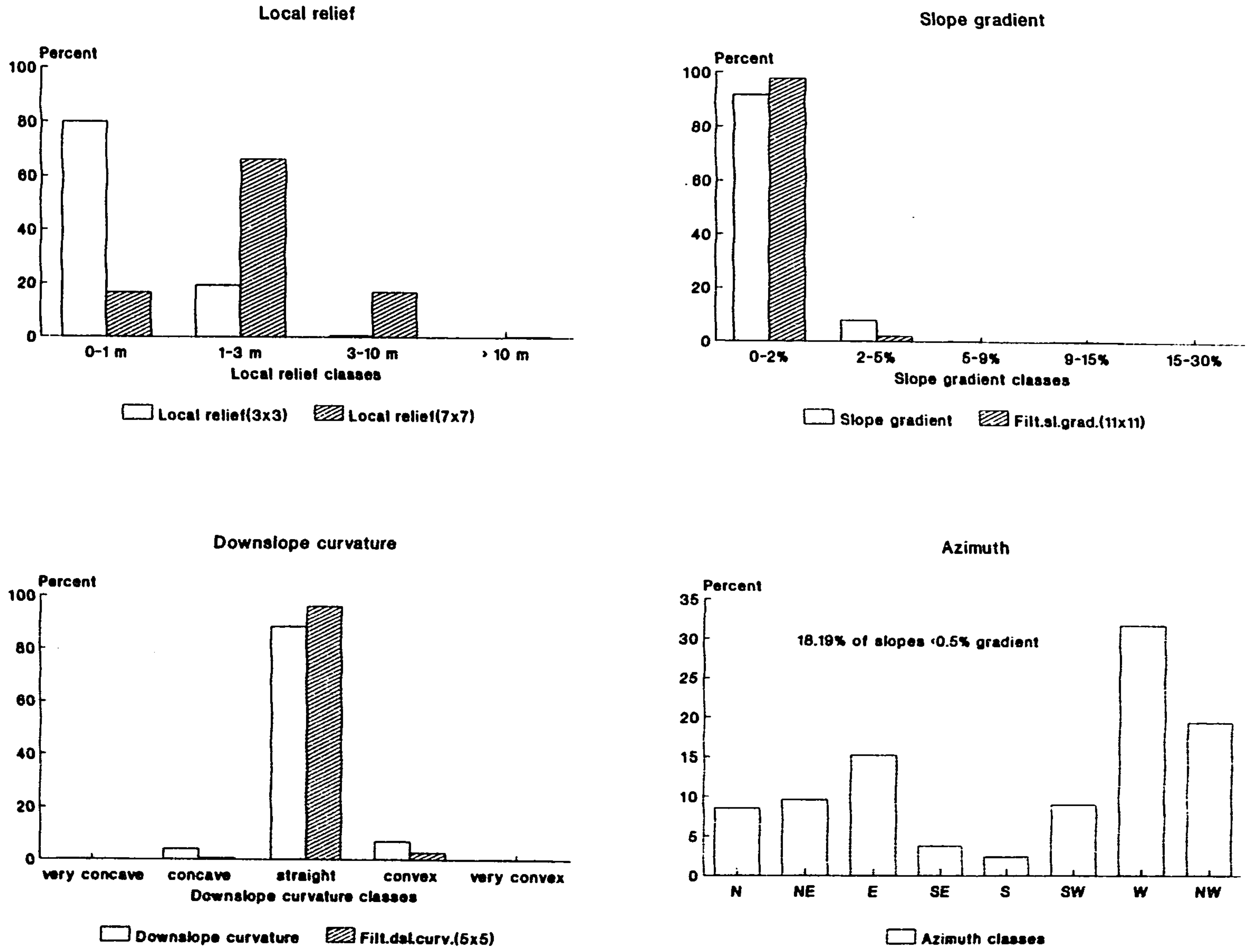


Figure A2.3.6. Classed frequency distribution of surficial geology landform category *flat-rolling(0-3m)*

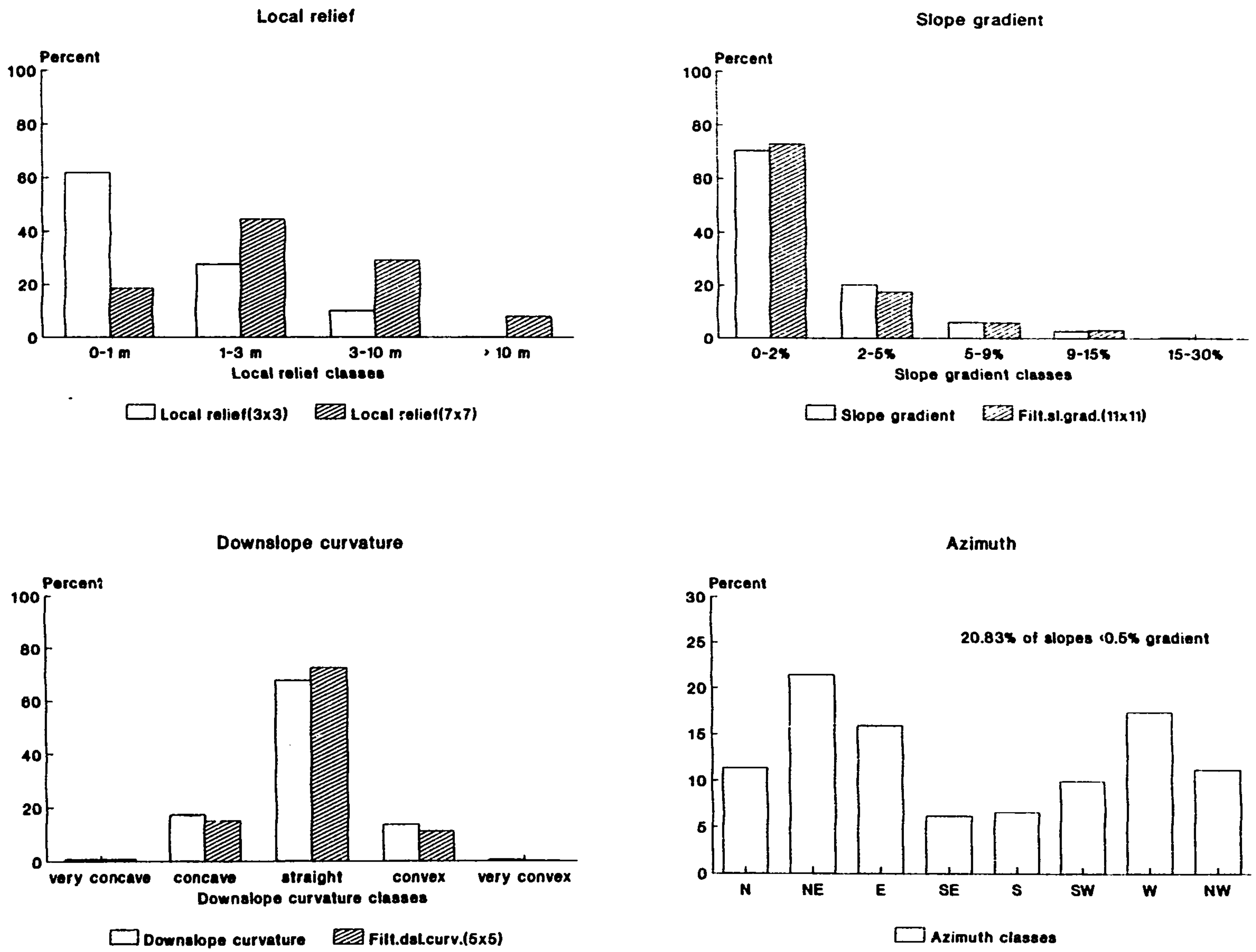


Figure A2.3.7. Classed frequency distribution of surficial geology landform category *rolling(1-3m)*

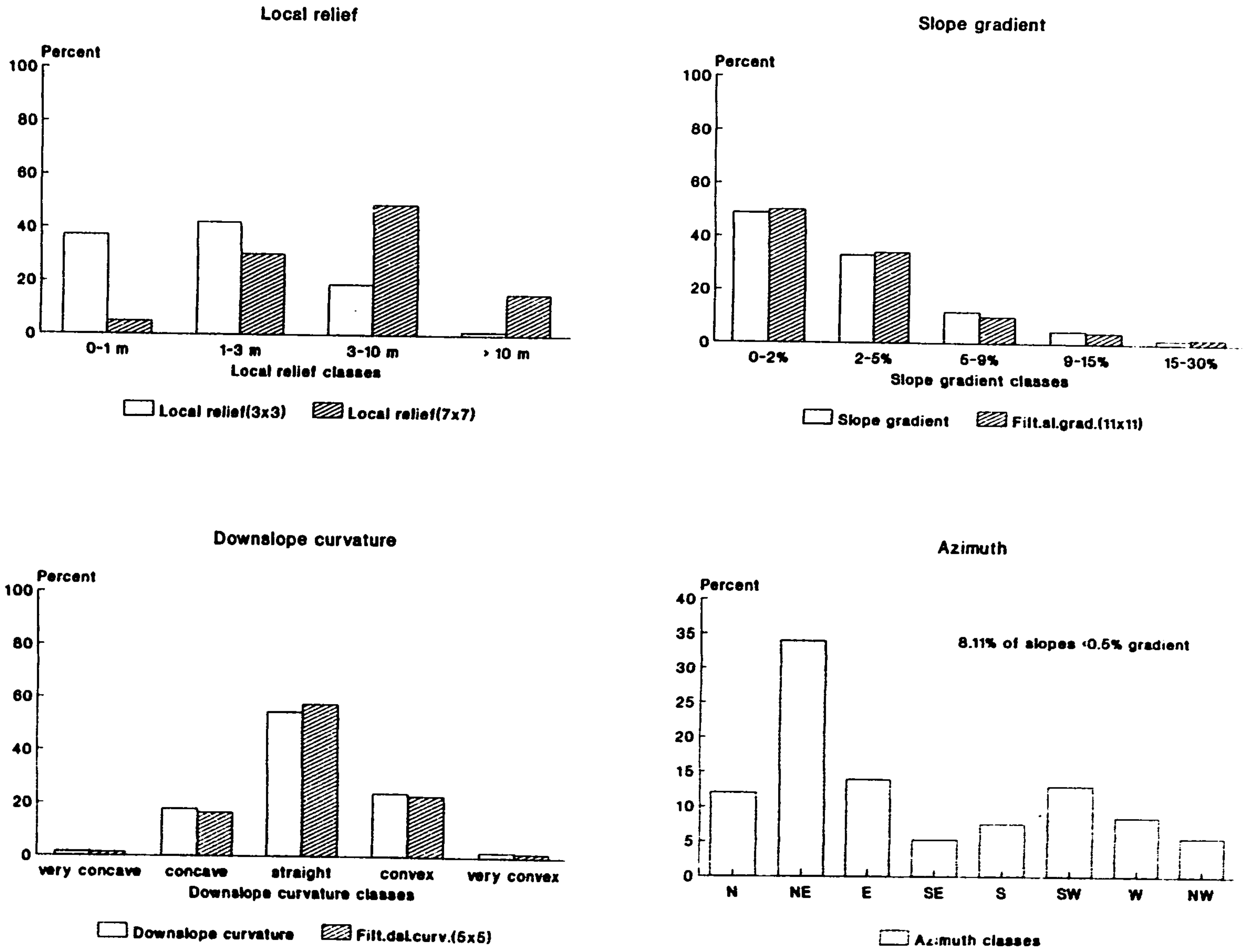


Figure A2.3.8. Classed frequency distribution of surficial geology landform category *rolling(3-10m)*

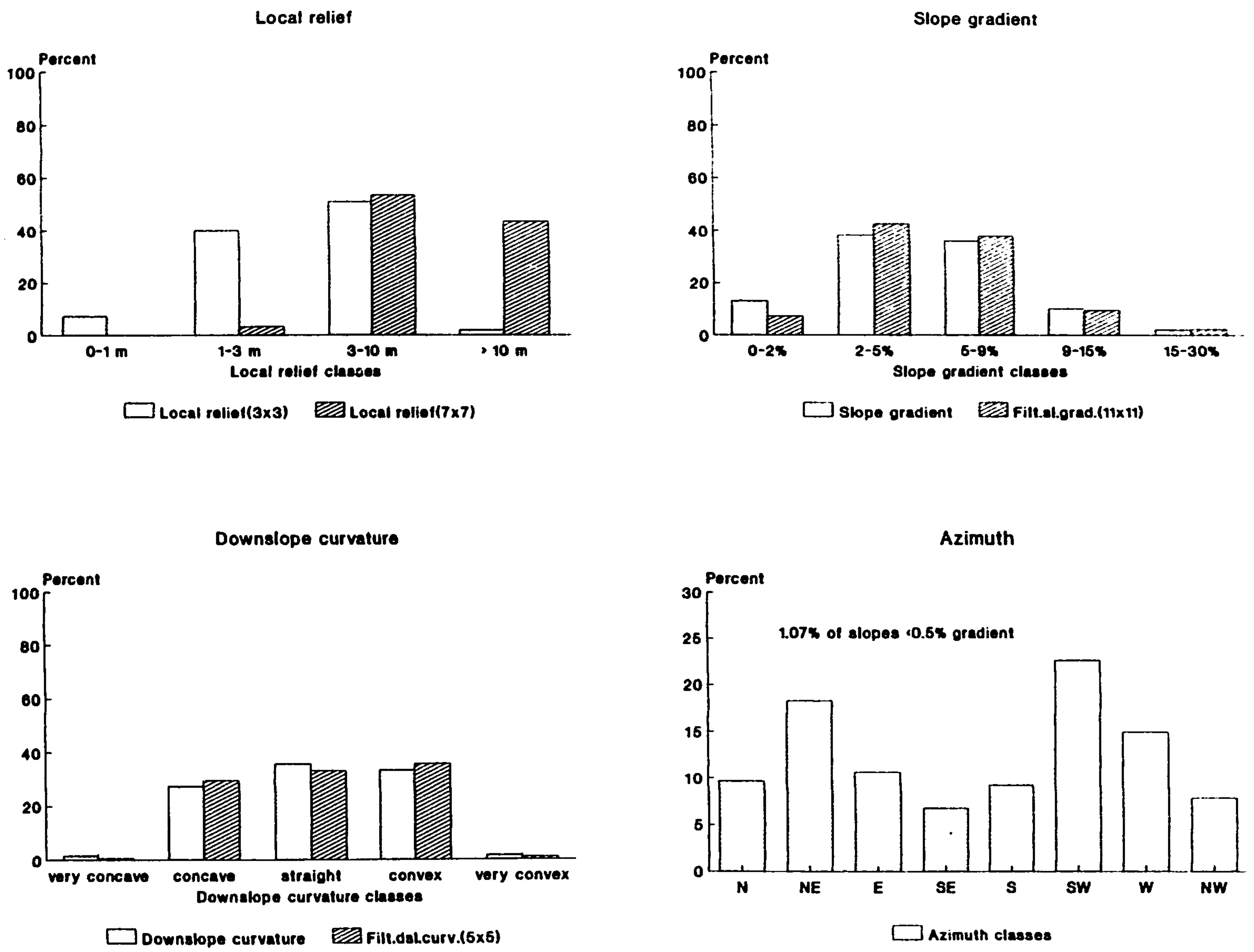


Figure A2.3.9. Classed frequency distribution of surficial geology landform category *rolling(> 10m)*

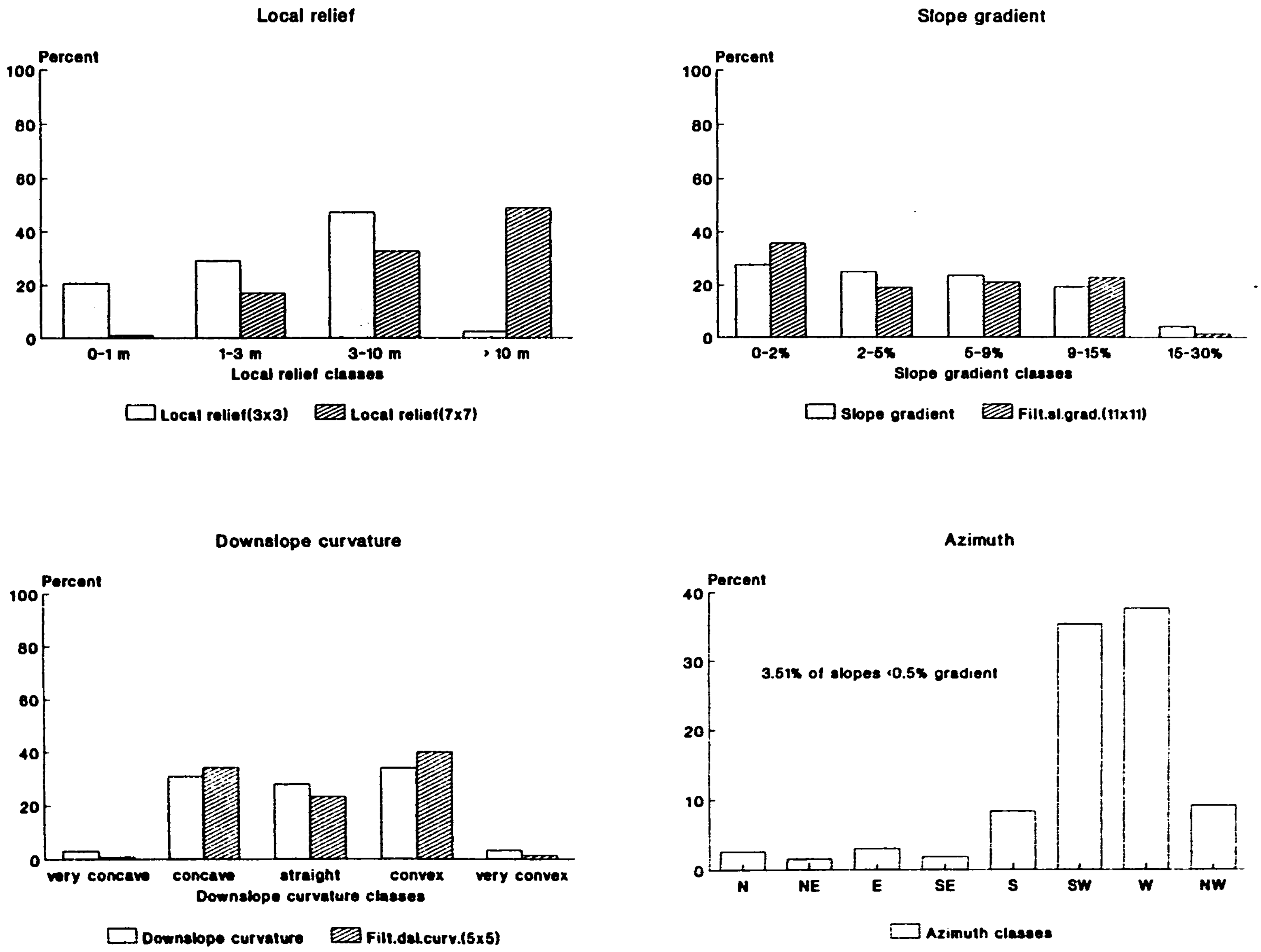


Figure A2.3.10. Classed frequency distribution of surficial geology landform category *hummocky(1-3m)*

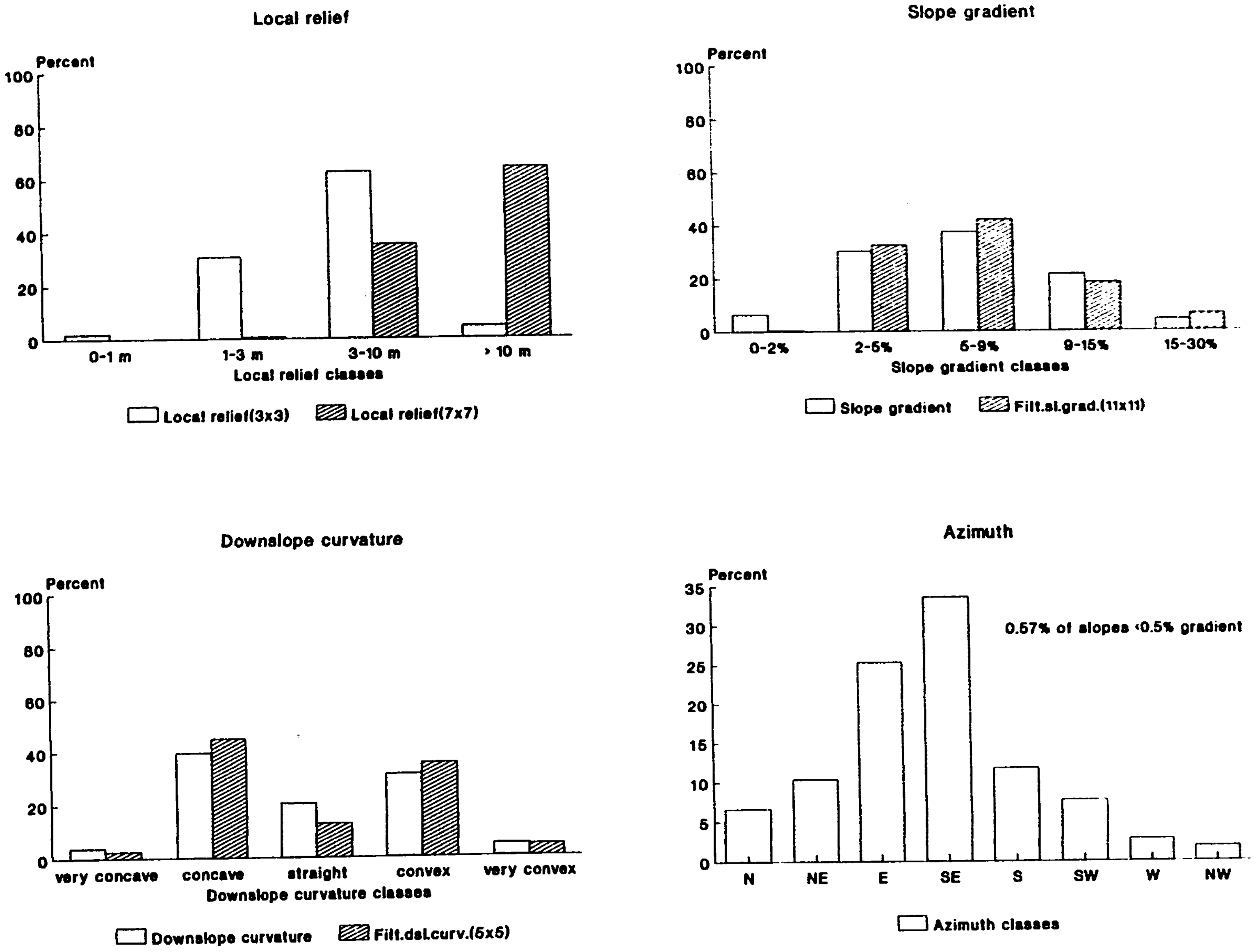


Figure A2.3.11. Classed frequency distribution of surficial geology landform category *hummocky(3-10m)*

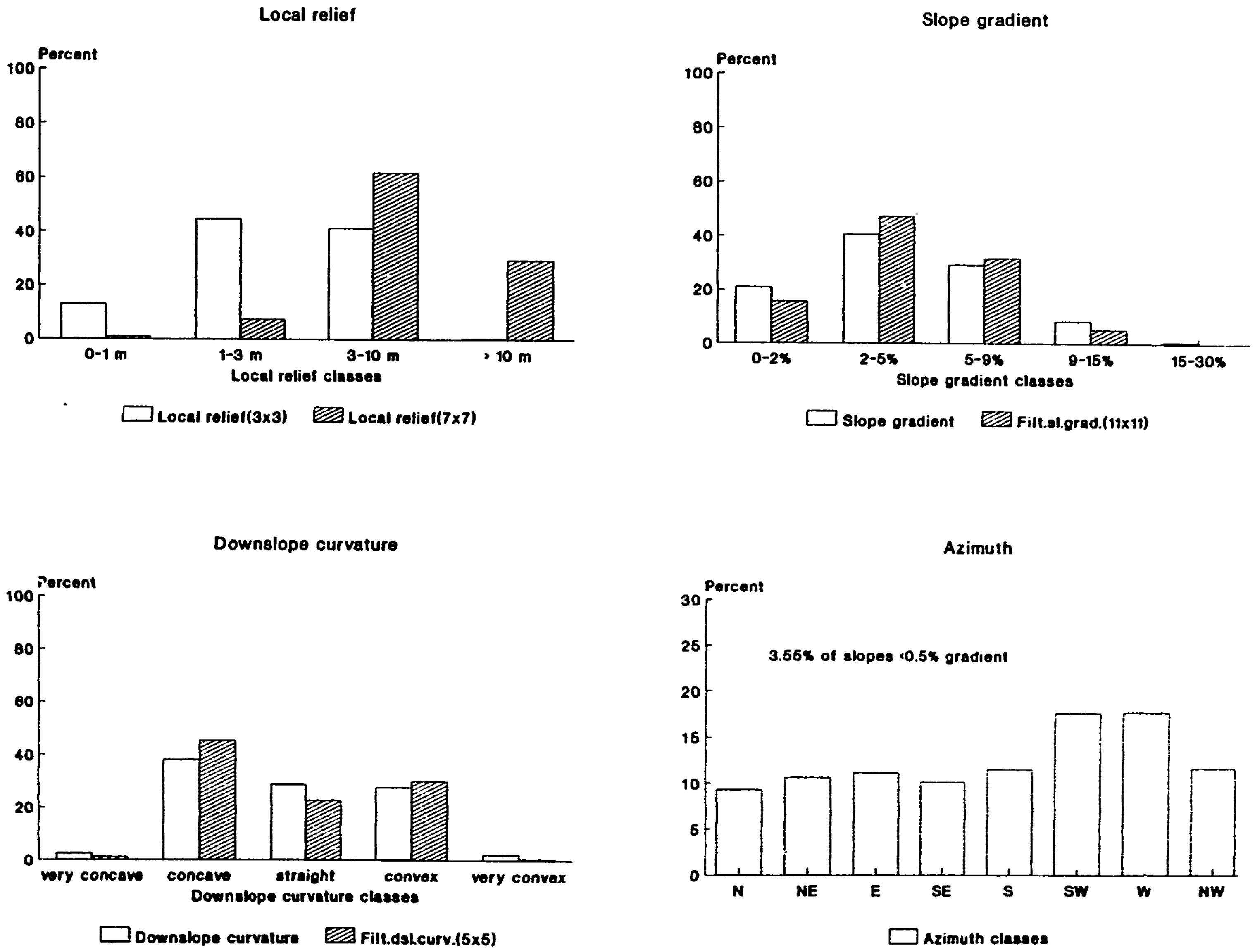


Figure A2.3.12. Classed frequency distribution of surficial geology landform category *hummocky(>3m)*

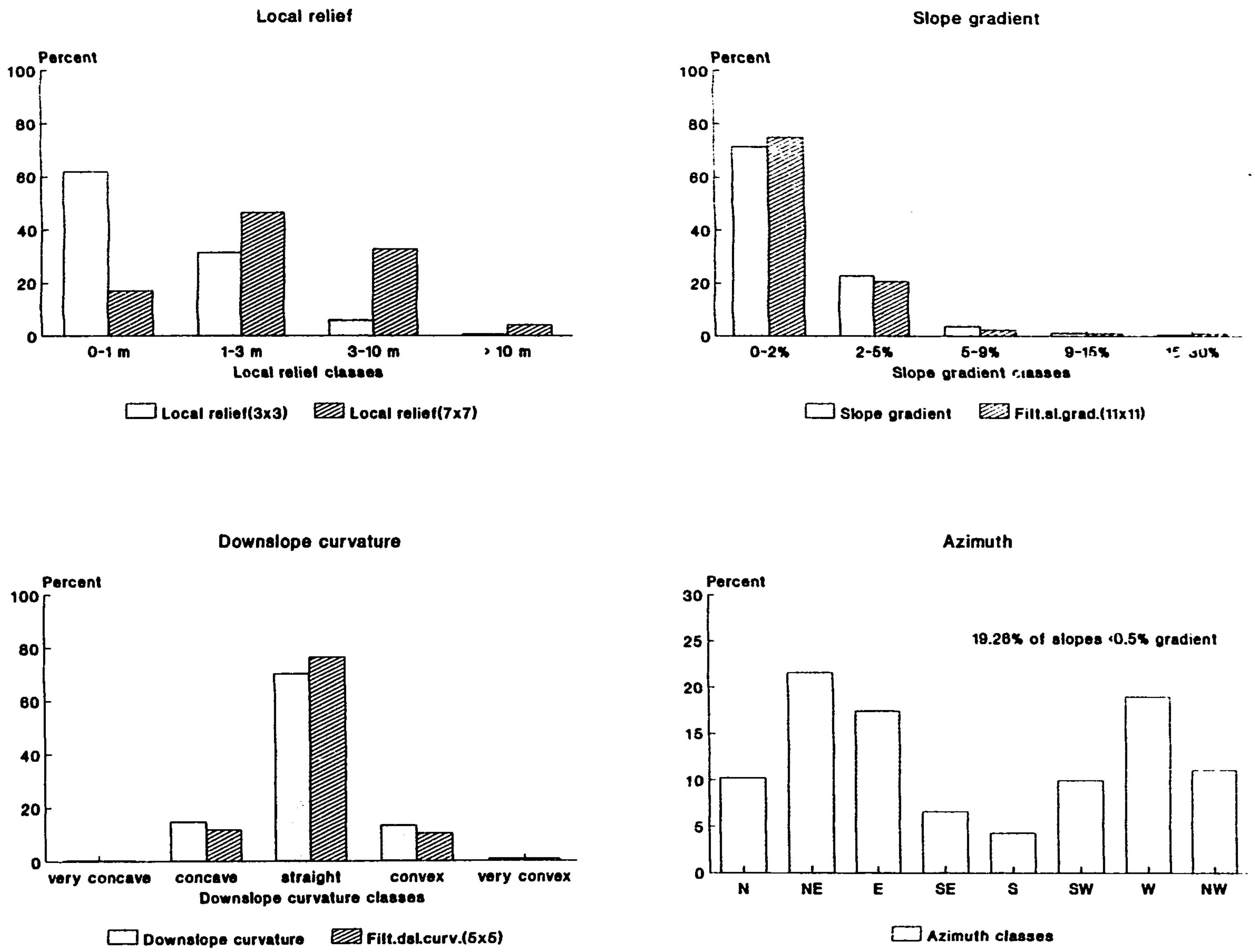


Figure A2.3.13. Classed frequency distribution of surficial geology landform category *hummocky-rolling(1-3m)*

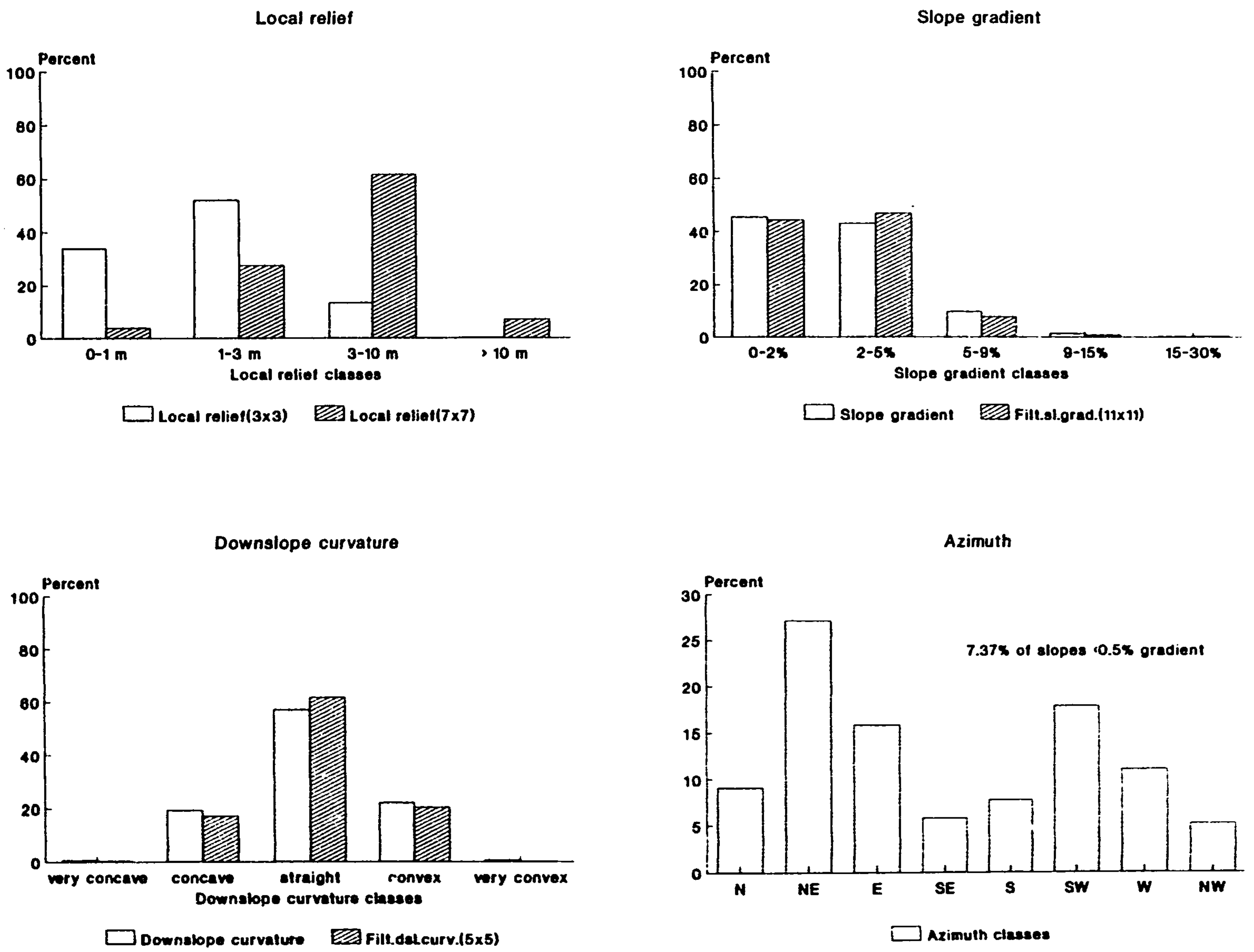


Figure A2.3.14. Classed frequency distribution of surficial geology landform category *hummocky-rolling(1-10m)*

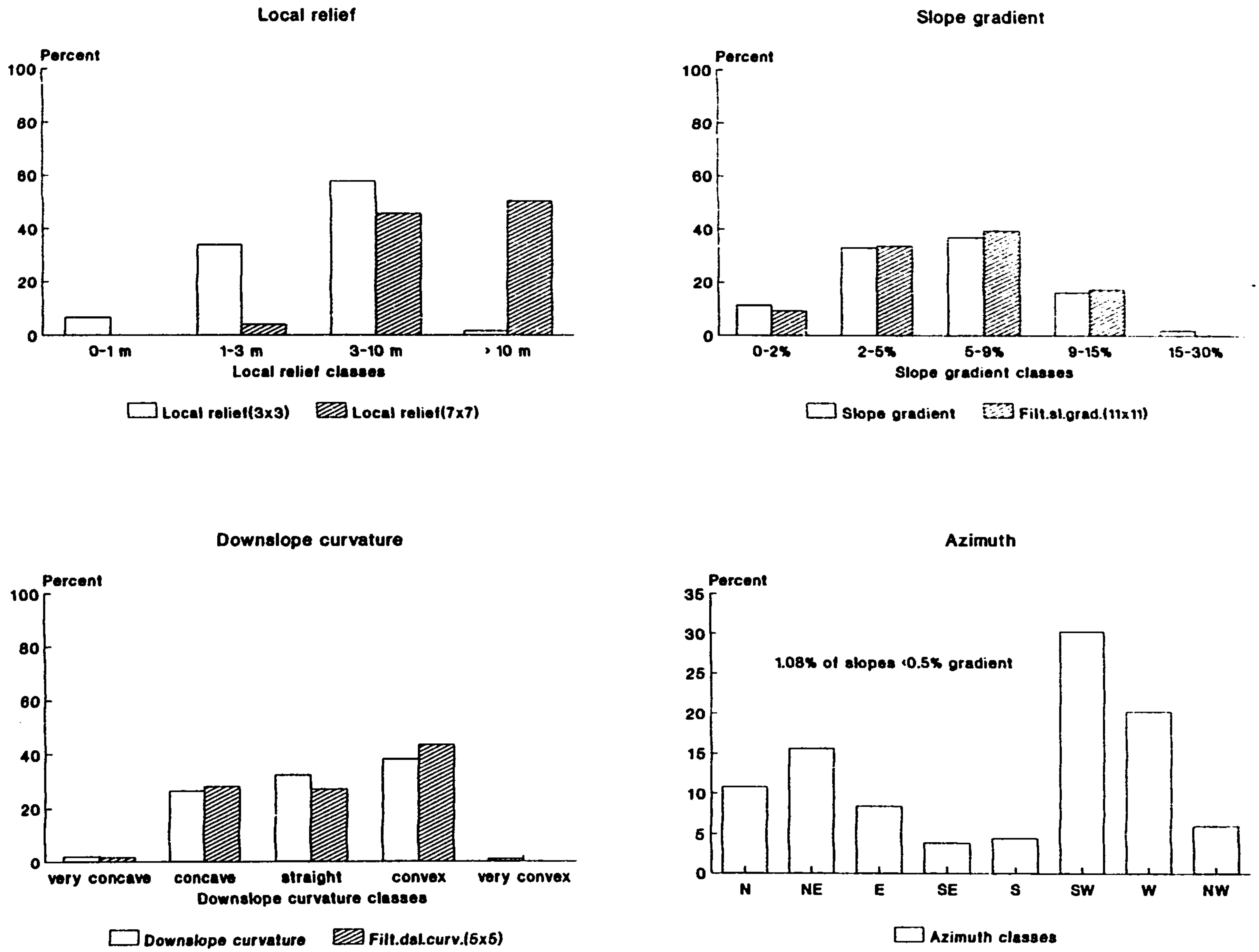


Figure A2.3.15. Classed frequency distribution of surficial geology landform category *hummocky-rolling(3-10m)*

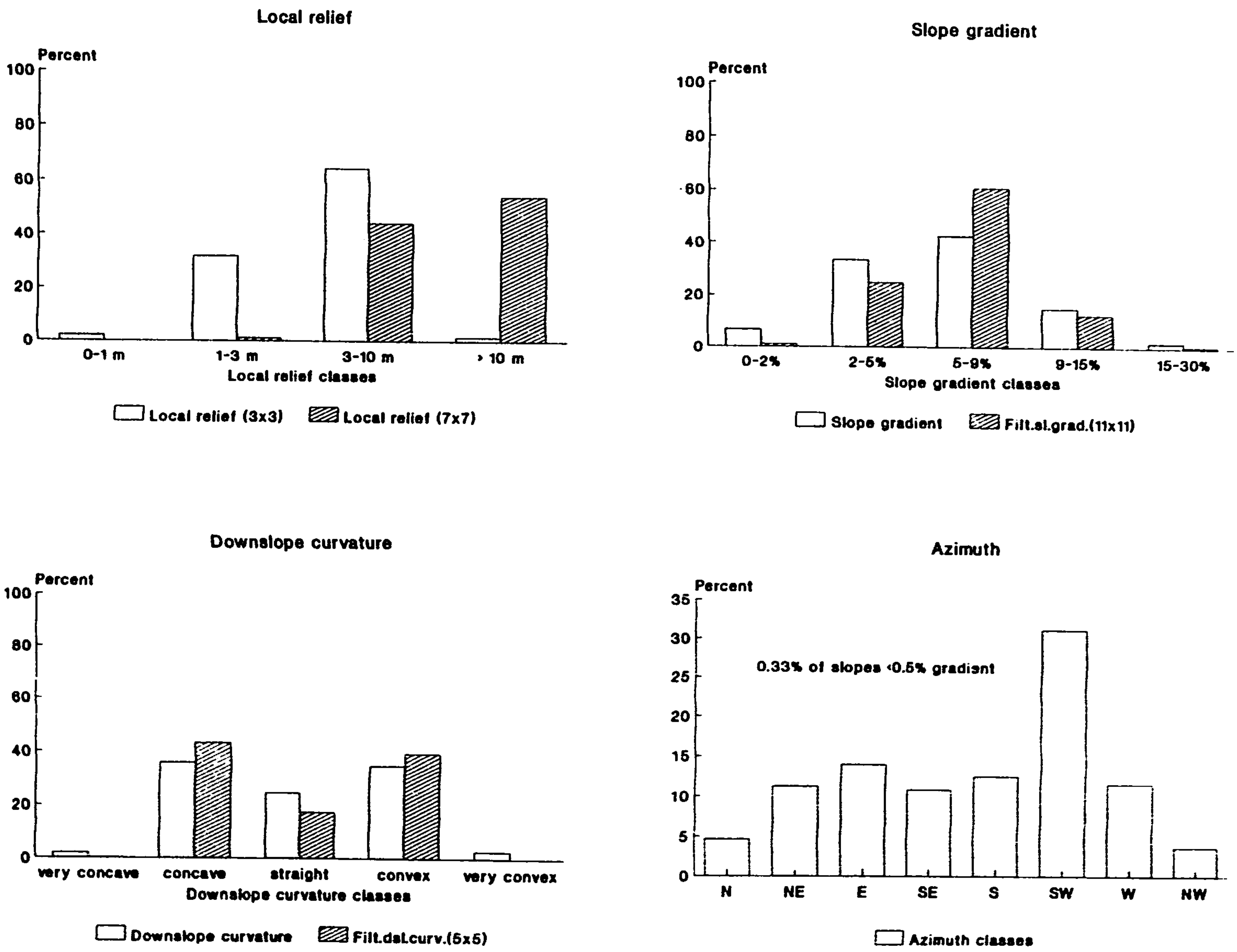


Figure A2.3.16. Classed frequency distribution of surficial geology landform category *hummocky-rolling(>3m)*

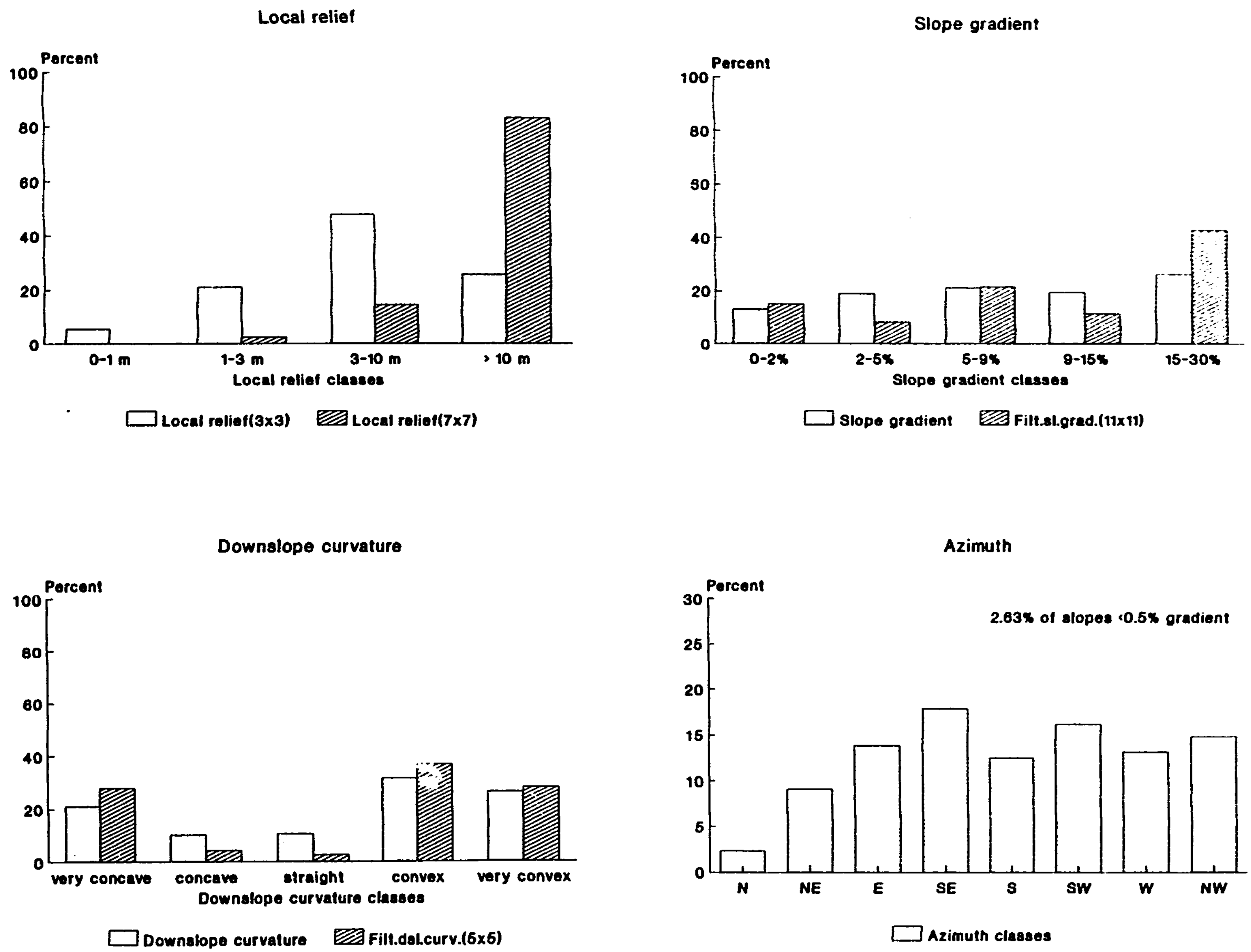


Figure A2.3.17. Classed frequency distribution of surficial geology landform category *hummocky-rolling(> 10m)*

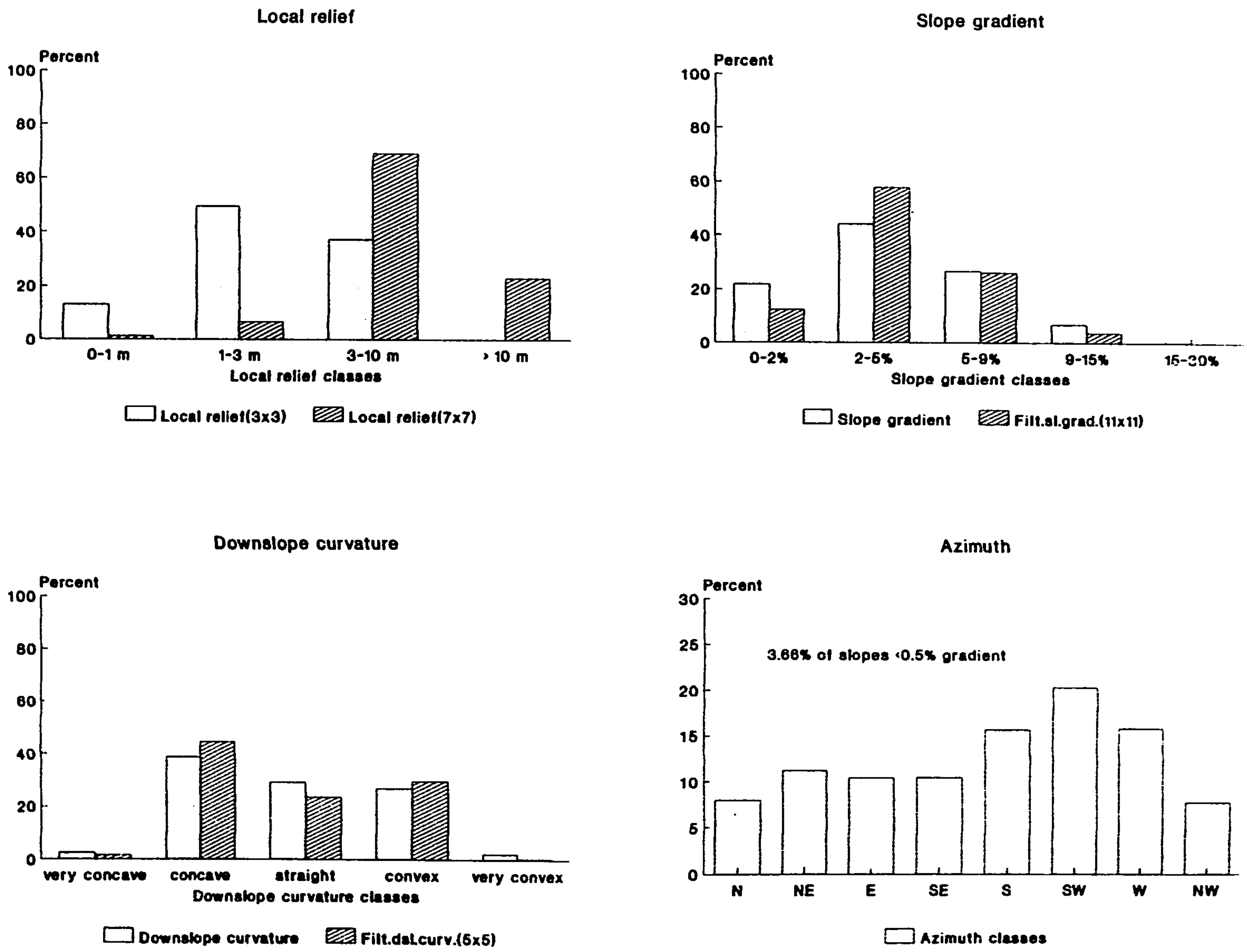


Figure A2.3.18. Classed frequency distribution of surficial geology landform category *hummocky-ridged(>3m)*

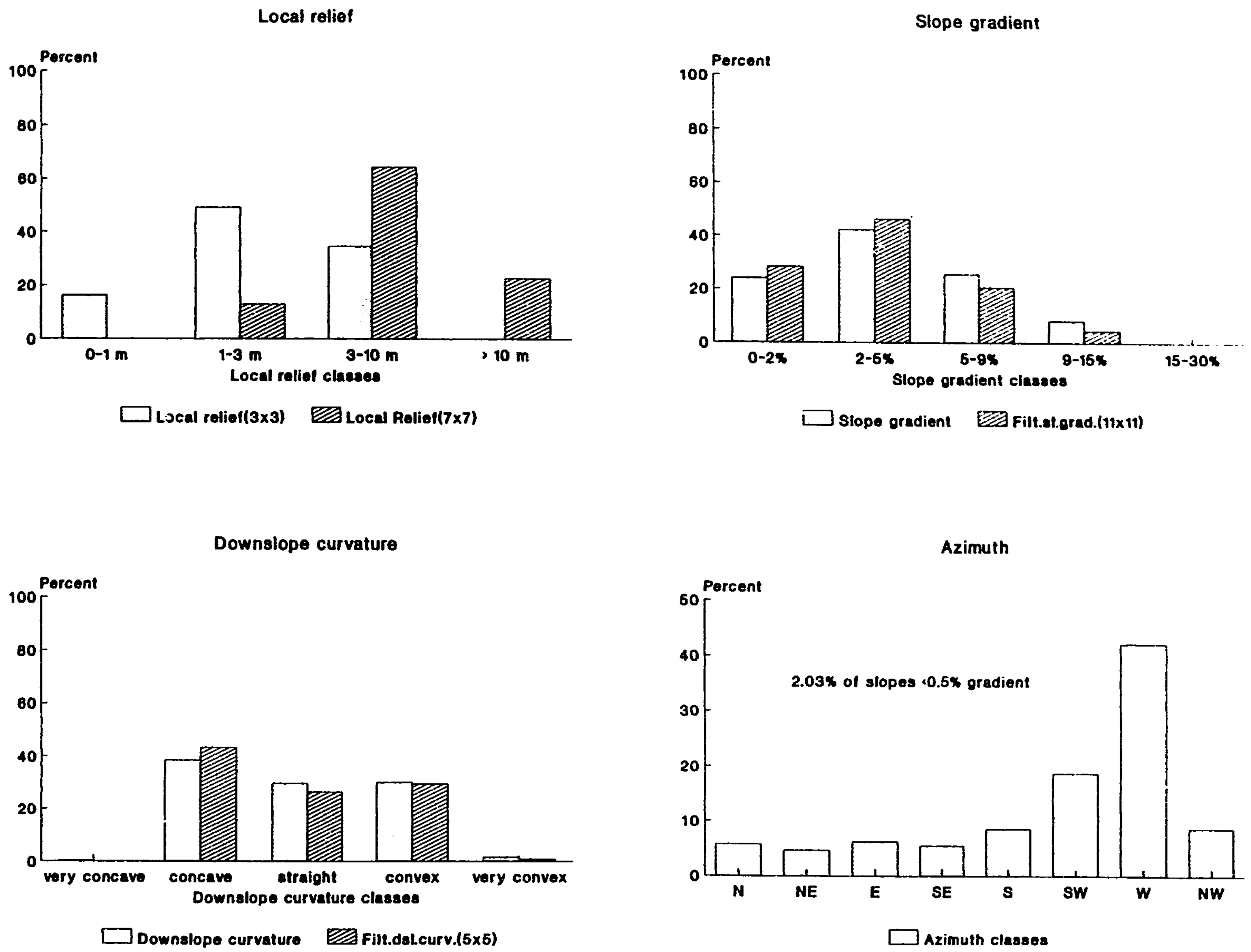


Figure A2.3.19. Classed frequency distribution of surficial geology landform category *ridged(3-10m)*

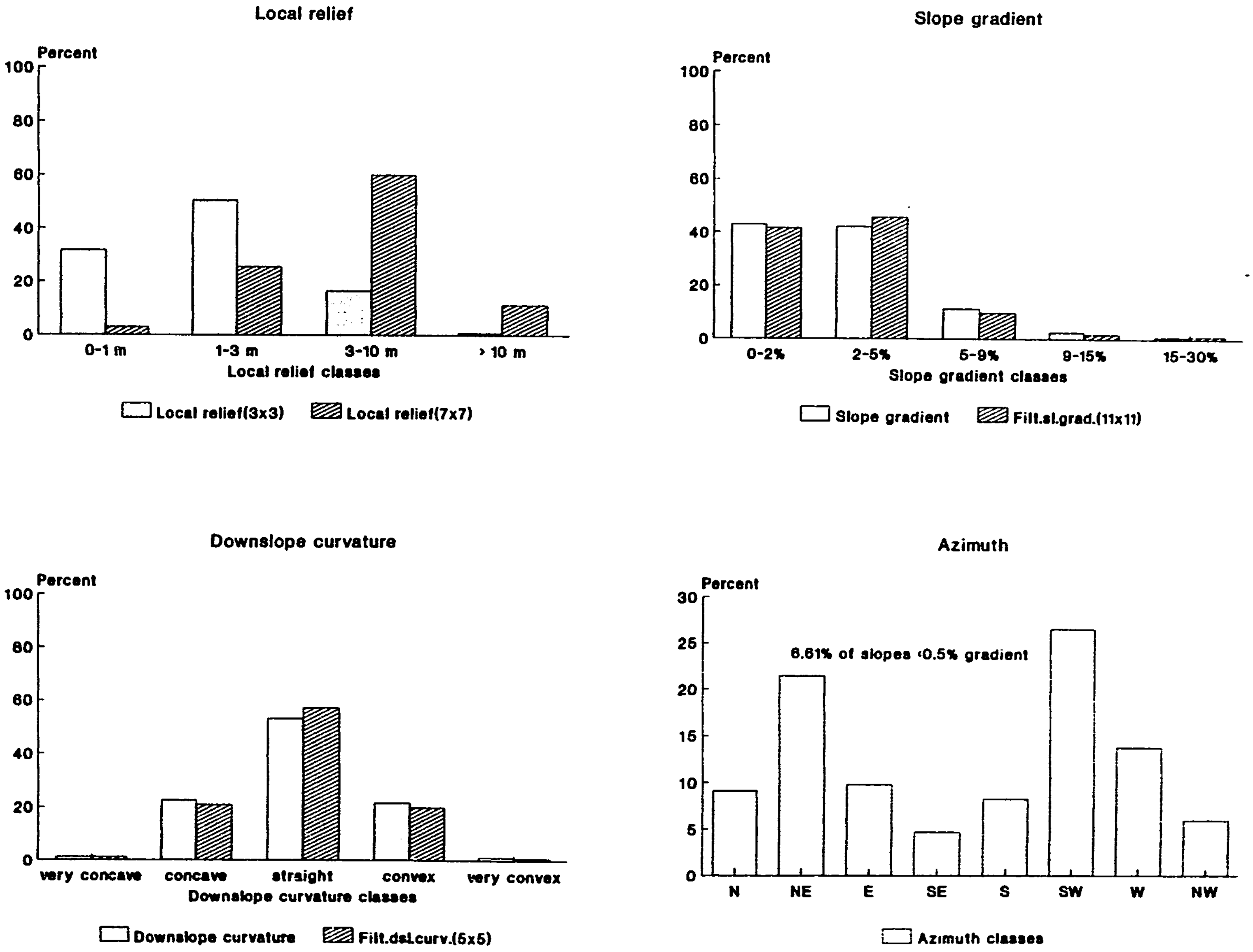


Figure A2.3.20. Classed frequency distribution of surficial geology landform category *ridged-rolling(3-10m)*

Legend for geology landform categories (Figures A2.4.1 to A2.4.3)

1 = lake, 2 = varied, 3 = terraced, 4 = flat, 5 = flat-hummocky, 6 = flat-rolling, 7 = rolling(1-3m), 8 = rolling(3-10m),
9 = rolling(>10m), 10 = hummocky(1-3m), 11=hummocky(3-10m), 12 = hummocky(>3m), 13 = hum-rolling(1-3m),
14 = hum-rolling(1-10m), 15 = hum-rolling(3-10m), 16 = hum-rolling(>3m), 17 = hum-rolling(>10m),
18 = hum-ridged(>3m), 19 = ridged(3-10m), 20 = ridged-rolling(3-10m)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1.00																			
2		1.00																		
3			1.00																	
4				1.00																
5	1.47				1.00															
6						1.00														
7				1.53			1.00													
8			1.64	1.08			1.65	1.00												
9			1.42	1.25				1.15	1.00											
10			1.06						1.50	1.00										
11			1.02					1.66	1.44	1.04	1.00									
12				1.46			1.05	1.58				1.00								
13							1.32					1.39	1.00							
14							1.42					1.50	1.08	1.00						
15			1.33	1.33				1.23	1.06	1.41	1.35				1.00					
16				1.20			1.28	1.30	1.49			1.22	1.69		1.59	1.00				
17		1.66	1.63							1.54	1.60						1.00			
18							1.31					1.38	1.01	1.08		1.68		1.00		
19				1.19			1.28	1.29	1.49			1.22	1.69		1.59	1.00		1.68	1.00	
20				1.40			1.09	1.52				1.04	1.44	1.55		1.17		1.43	1.17	1.00

Figure A2.4.1. Matrix of F-test results for local relief(7x7) distributions between geology landform categories at significance level < 1%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1.00																			
2		1.00																		
3			1.00																	
4				1.00																
5	1.56				1.00															
6	1.62					1.00														
7				1.39			1.00													
8				1.35				1.00												
9				1.48				1.10	1.00											
10			1.14						1.57	1.00										
11			1.00							1.14	1.00									
12				1.08			1.50	1.25	1.37			1.00								
13				1.55			1.12					1.67	1.00							
14				1.70			1.22						1.10	1.00						
15				1.42				1.05	1.04	1.63		1.32			1.00					
16				1.24				1.09	1.20			1.15			1.15	1.00				
17																	1.00			
18				1.11			1.25	1.50	1.64			1.20	1.40	1.54	1.58	1.37		1.00		
19				1.01			1.37	1.37	1.50			1.10	1.53	1.67	1.44	1.26		1.09	1.00	
20				1.00			1.39	1.35	1.48			1.08	1.55	1.70	1.42	1.24		1.11	1.01	1.00

Figure A2.4.2. Matrix of F-test results for slope gradient distributions between geology landform categories at significance level < 1%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1.00																			
2		1.00																		
3		1.20	1.00																	
4				1.00																
5	1.28				1.00															
6	1.39				1.09	1.00														
7				1.13			1.00													
8								1.00												
9								1.29	1.00											
10								1.29	1.67	1.00										
11		1.09	1.10								1.00									
12								1.02	1.32	1.26		1.00								
13				1.20			1.36		1.58				1.00							
14				1.10			1.03						1.32	1.00						
15								1.38	1.07			1.41	1.46		1.00					
16								1.08	1.37	1.22		1.04			1.46	1.00				
17																	1.00			
18								1.02	1.26	1.32		1.05			1.35	1.08		1.00		
19				1.41			1.59		1.33				1.17	1.55	1.24			1.68	1.00	
20								1.12	1.15	1.45		1.14			1.23	1.19		1.10	1.53	1.00

Figure A2.4.3. Matrix of F-test results for downslope curvature distributions between geology landform categories at significance level < 1%

Legend for soil and geology landform categories (Figures A2.5.1 to A2.5.3)

horizontal soil categories:
1 = lake, 2 = level(0-2%), 3 = level(0-10%), 4 = undulating(0-5%), 5 = undulating (2-5%),
6 = dissected(>5%), 7 = dissected(>10%), 8 = hum-inclined(>9%), 9 = hum=inclined(>15%),
10 = hum=ridged(5-9%), 11 = hum-ridged(9-15%), 12=hummocky(5-9%), 13 = hummocky(9-15%),
14 = hummocky(>15%), 15 = hummocky(5-15%)

vertical geology landform categories:
1 = lake, 2 = varied, 3 = terraced, 4 = flat, 5 = flat-hummocky, 6 = flat-rolling, 7 = rolling(1-3m), 8 = rolling(3-10m),
9 = rolling(>10m), 10 = hummocky(1-3m), 11=hummocky(3-10m), 12 = hummocky(>3m), 13 = hum-rolling(1-3m),
14 = hum-rolling(1-10m), 15 = hum-rolling(3-10m), 16 = hum-rolling(>3m), 17 = hum-rolling(>10m),
18 = hum-ridged(>3m), 19 = ridged(3-10m), 20 = ridged-rolling(3-10m)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.01	1.66		1.03	1.64					1.65					1.26
2															
3			1.62				1.14							1.68	
4			1.10			1.03		1.18	1.07				1.39	1.06	
5	1.48	1.13		1.51	1.12					1.12		1.64			
6															
7			1.67			1.58		1.30	1.43		1.33	1.58	1.10	1.61	
8			1.01			1.05		1.28	1.15				1.50	1.03	
9			1.14			1.21	1.62	1.47	1.33					1.18	
10							1.06								
11			1.64				1.13								
12			1.59			1.50		1.23	1.36		1.40	1.66	1.05	1.54	
13											1.01	1.19	1.45		
14		1.61			1.62					1.61	1.07	1.11	1.57		
15			1.21			1.29	1.52	1.57	1.42					1.26	
16			1.31			1.24		1.01	1.12				1.16	1.26	
17							1.42								
18											1.01	1.20	1.44		
19			1.31			1.23		1.01	1.12				1.16	1.26	
20			1.54			1.45		1.19	1.31		1.45		1.01	1.48	

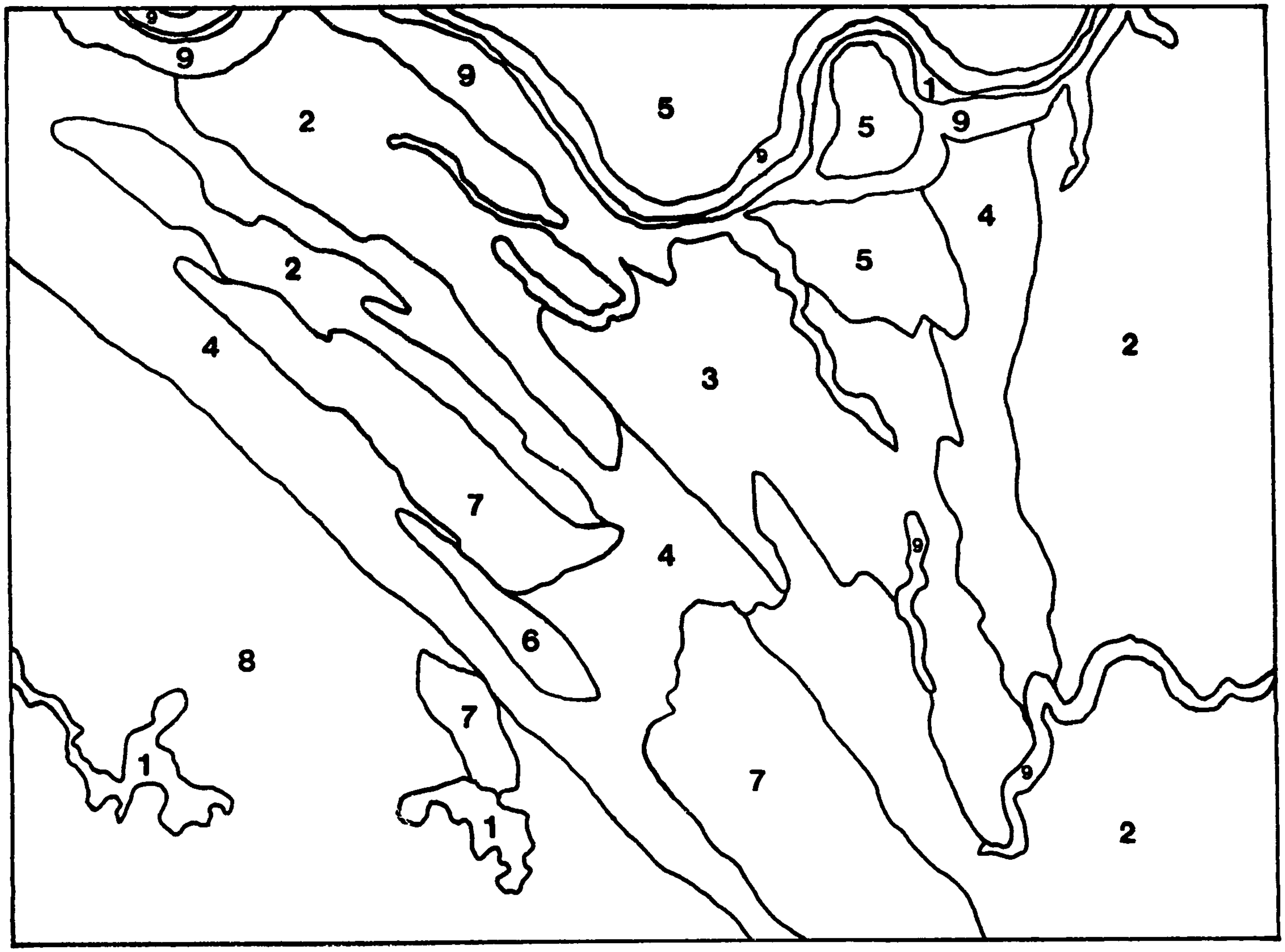
Figure A2.5.1. Matrix F-test results for local relief(7x7) distributions between soil and geology landform categories at significance level < 1%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.09			1.31											1.15
2						1.14									
3			1.59			1.69	1.00							1.60	
4			1.67					1.18	1.40				1.06	1.66	
5	1.43	1.27			1.31					1.41					1.36
6				1.24											
7								1.64			1.31	1.31	1.47		
8			1.23					1.15	1.04				1.28	1.22	
9			1.12					1.25	1.08				1.40	1.12	
10			1.39				1.14		1.66					1.40	
11			1.59			1.69	1.00							1.60	
12			1.54					1.09	1.30				1.02	1.53	
13										1.70	1.18	1.18	1.64		
14					1.66					1.55	1.07	1.07			
15			1.17					1.2:	1.01				1.35	1.16	
16			1.34					1.05	1.13				1.17	1.34	
17															
18								1.31	1.55		1.65	1.65	1.17		
19			1.69					1.20	1.42				1.07	1.68	
20			1.67					1.18	1.40				1.06	1.66	

Figure A2.5.2. Matrix of F-test results for slope gradient distributions between soil and geology landform categories at significance level < 1%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.12	1.55													1.04
2			1.25				1.38							1.67	
3			1.04				1.15							1.39	
4					1.36					1.28	1.32	1.09			
5	1.43														1.33
6	1.56														1.45
7					1.20					1.13	1.16	1.04			
8								1.11	1.04				1.06	1.67	
9								1.44	1.34				1.20		
10							1.57	1.16	1.24				1.40	1.30	
11			1.14				1.26							1.53	
12								1.09	1.02				1.11	1.64	
13					1.63					1.54	1.58	1.31			
14					1.24					1.17	1.20	1.01			
15								1.54	1.43				1.28		
16								1.05	1.02				1.14	1.58	
17															
18								1.14	1.06				1.06		
19												1.53	1.59		
20								1.25	1.16				1.04		

Figure A2.5.3. Matrix of F-test results for downslope curvature distributions between soil and geology landform categories at significance level < 1%



1 = Lake, Level 2 = Undulating 3 = Rolling 4 = Hummocky-Rolling (medium relief) 5 = Hummocky-Rolling (high relief)
6 = Ridged 7 = Hummocky-Ridged 8 = Hummocky 9 = Dissected

Transparency. Map of surface expression interpreted from DTM images