Terrain synthesis : the creation, management, presentation and validation of artificial landscapes

by

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"Non omnia possumus omnes"

Virgil, The Aeneid

"Look at me. I design coastlines. I got an award for Norway . . . I've been doing fjords all my life"

Slartibartfast, in *The Hitchhiker's Guide to the Galaxy* (Adams 1983)

University of Nottingham

ABSTRACT

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'Synthetic Terrain' is the term used for artificially-composed computer-based Digital Terrain Models (DTMs) created by a combination of techniques and heavily influenced by Earth Sciences applications. The synthetic landscape is created to produce 'geographically acceptable', 'realistic' or 'valid' computer-rendered landscapes, maps and 3D images, which are themselves based on synthetic terrain Digital Elevation Models (DEMs). This thesis examines the way in which mainly physical landscapes can be synthesised, and presents the techniques by which terrain data sets can be managed (created, manipulated, displayed and validated), both for academic reasons and to provide a convenient and cost-effective alternative to expensive 'real world' data sets. Indeed, the latter are collected by ground-based or aerial surveying techniques (e.g. photogrammetry), normally at considerable expense, depending on the scale, resolution and type required. The digital information for a real map could take months to collect, process and reproduce, possibly involving demanding Information Technology (IT) resources and sometimes complicated by differing (or contradictory) formats. Such techniques are invalid if the region lies within an 'unfriendly' or inaccessible part of the globe, where (for example), overflying or ground surveys are forbidden. Previous attempts at synthesising terrain have not necessarily aimed at realism. Digital terrain sets have been created by using fractal mathematical models, as 'special effects' for the entertainment industry (e.g. science fiction 'alien' landscapes' for motion pictures and arcade games) or for artistic reasons. There are no known examples of synthesised DTMs being created with such a wide range of requirements and functionality, and with such a regard to validation and realism.

This thesis addresses the whole concept of producing 'alternative' landscapes in artificial form - nearly 22 years of research aimed at creating 'geographically-sensible' synthetic terrain is described with the emphasis on the last 5 years, when this PhD thesis was conceived. These concepts are based on radical, inexpensive and rapid techniques for synthesising terrain, yet value is also placed on the 'validity', realism and 'fitness for purpose' of such models. The philosophy - or the 'thought processes' - necessary to achieve the development of the algorithms leading to synthesised DTMs is one of the primary achievement of the research. This in turn led to the creation of an interactive software package called GEOFORMA, which requires some manual intervention in the form of preliminary terrain classification. The sequence is thus: the user can choose to create terrain or landform assemblages without reference to any real world area. Alternatively, he can select a real world region or a 'typical' terrain type on a 'dial up' basis, which requires a short period of intensive parametric analysis based on research into established terrain classification techniques (such as fractals and other mathematical routines, process-response models etc.) . The creates a composite synthesised terrain model of high quality and realism, a factor examined both qualitatively and quantitatively. Although the physical terrain is the primary concern, similar techniques are applied to the human landscape, noting such attributes as the density, type, nature and distribution of settlements, transport systems etc., and although this thread of the research is limited in scope compared with the physical landscape synthesis, some spectacular results are presented. The system also creates place names based on a simple algorithm. Fluvial landscapes, upland regions and coastlines have been selected from the many possible terrain types for 'treatment', and the thesis gives each of these sample landscapes a separate chapter with appropriate illustrations from this original and extensive research. Finally, and inevitably, the work also poses questions in attempting to provide answers, this is perhaps inevitable in a relatively new genre, encompassing so many disciplines, and with relatively sparse literature on the subject.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFV	Armoured Fighting Vehicle
AGV	Autonomous Guided Vehicle
AI	Artificial Intelligence
AOR	Area of Responsibility
AT	Anti-Tank
ATGM	Anti-Tank Guided Missile
ATGW	Anti-Tank Guided Weapon
AZ	Azimuth
BP or b.p.	Before Present
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
Casevac	Casualty Evacuation
COM	Common Object Model
COTS	Commercial off-the-shelf
CPT	Central Place Theory
CSIRO	Australian land evaluation organisation (unknown)
DEC	Digital Equipment Corporation (now part of Compaq Corporation)
DEM	Digital Elevation Model
DERA	Defence Establishment for Research and Analysis (UK MOD)
DFAD	Digital Feature Analysis Data
dfm	degrees of freedom model (i.e. a 6 dfm would have motion and rotation about the Cartesian (x,y,z) axes and corresponds to a model of a particle's movement in space). This is common way of modelling a moving object in 3D space.
DGM	Digital Ground Model
DHM	Digital Height Model
DLMS	Digital Landmass System
DoD	Department of Defense (US)
DMA	Defense Mapping Agency (US)
D.Mil.Svy.	Department of Military Survey (UK MOD)
DOD	(or DoD) US Department of Defense
DTED	Digital Terrain Elevation Data
DTM	Digital Terrain Model

e	Prefix to words like 'Architect' to imply electronic/internet element (e.g. eArchitect, eCommerce etc.)
EL	Elevation
ESRI	Environmental Systems Research Institute
GCS	Global Co-ordinate System
GUI	Graphical User Interface
HMG	Her Majesty's Government
HUD	Head-up Display
IP	Internet Protocol
IS	Information Systems
IT	Information Technology
IWM	Imperial War Museum
LAN	Local Area Net (work)
Lidar or LIDAR	Light detection and ranging
MHz	MegaHertz
MIPS	Millions of instructions per second
MIT	Massachusetts Institute of Technology (US)
MOD	Ministry of Defence
NATO	North Atlantic Treaty Organisation
NT	An operating system copyrighted to the Microsoft Corporation
ONC	Operational Navigational Chart
OO	Object Oriented
OOD	Object Oriented Design
Oracle SD	The Spatial Data sub-module used by the Oracle RDBMS system
OS (1)	Ordnance Survey (UK 'official' map surveyors and government cartographers)
OS (2)	(Computer) Operating System (such as NT, UNIX, Linux, VMS etc.)
OSF	Open Software Foundation
PC	Personal Computer
POVRAY	Also POV : A 3D rendering visualisation package

PUCE	Pattern Unit Component Evaluation
RAD	Rapid Application Design
RARDE	Royal Armament Research and Development Establishment (now called DERA)
RARDE (Ch)	Royal Armament Research and Development Establishment (Chertsey)
RARDE (FH)	Royal Armament Research and Development Establishment (Fort Halstead)
RCI	Rating Cone Index
RDBMS	Relational Database Management System
Q	Term used by geomorphologists/ hydrologists for stream discharge (units/time)
SCISSORS	Synthesised Coastline Initialisation, Synthesis, Storage and Object Representation System
SIG	Special Interest Group
SNE	Synthetic Natural Environment
SSADM	Structured Systems Analysis and Design Methodology
SQL	Structured Query Language
STDRD	Synthetic terrain development, research and database
TCV	Terrain conformity value
TPC	Tactical Pilotage Chart (Copyright HMSO London) Revised 1984
TRRL (now TRL)	Transport and Road Research Laboratory
UMV	Unmanned Vehicle (UK MOD Project using synthesised terrain)
URL	Universal Resource Locator (web address system)
USDA	US Department of Agriculture
USAEWES	US Army Engineer Waterways Experimental Station

WAN	Wide Area Net (or Network)
WWW	World-Wide Web (Global Internet sites and their connectivity)

GLOSSARY

ArcInfo	GIS Package (also ArcView)
Dial-up method	The concept of using small-scale maps to create an area which can, through terrain evaluation methods, produce an 'imaginary' landscape that statistically and subjectively 'mirrors' the original, and yet is completely fictional.
eCommerce	Electronic Commerce (see 'e')
GEOFORM	Original drainage computer model (written by Griffin 1997)
GEOFORMA	The name given to a proprietary software package used to create synthesised terrain in this thesis
GEOMIX	See GEOFORM
Geomorphologically-sensible	Implies that the synthesised terrain set is 'geomorphologically viable' and would pass a test specially devised for the purpose
Internet	Loosely-coupled world network system (see 'i')
Intranet	Multiple usage of internet capability to allow world-wide web nodes (WWW) etc.
Kriging	A method of interpolation for geographical data systems named after the mining engineer Krige

Linux	An operating system from the 1990s and 2000 onwards
MapInfo	Commercial GIS product
Oracle	A world-wide corporation and the name of their sophisticated RDBMS product suite
Oracle SD	The Spatial Data sub-module used by the Oracle RDBMS system
Synthesised terrain	DTMs or DEMs created artificially
Wizard	Term coined by the Microsoft Corporation to describe an interactive GUI window that can take the user through stages until a task (such as installing a new printer) is performed. Wizards are associated with MS Windows and NT, and can be useful tools when they work correctly.
X, Y, Z	Cartesian Co-ordinate system where X is 'north', Y is 'east' and Z is the vertical axis. Usually employed with an origin at (0, 0, 0). Lower case (x, y and z) also used. Sometimes the Z axis is negative 'upwards' (for aerospace usage).
x, y, z	See above ('Right-handed' set)
X, Z	Terms used in super-ellipsoid creation, not to be confused with Cartesian co-ordinates. Where there is a possibility of confusion in this thesis the difference is made clear.

CHAPTER ONE : INTRODUCTION

Chapter One Introduction

1.0 INTRODUCTION

This thesis is concerned with research leading to the modelling of synthesised terrain. Such simulated terrain is required for a number of reasons, and the research has set out to make the synthesised terrain models as 'real' as possible. This is clearly a large undertaking; one might ask: why bother to synthesise terrain when many Digital Terrain Models (DTMs) and Digital Elevation Models (DEMs) already exist? Why not use the real world - why go to all the trouble of trying to establish 'geomorphologically-viable' models? And even if this is possible, what types of landscapes should be created? At what scale and resolution? And how can synthesised terrain be validated? The thesis attempts to resolve these issues based on over 20 years of research into terrain modelling generally, and several years of practical methods of synthesising 'realistic' or geomorphologically-correct terrain. Some attempt is also made to synthesise man-made terrain or 'settlements and infrastructure' in the research, in order to represent 'true' topography (which strictly speaking includes more than just the bare form of the ground to include man-made features). This is essentially a subsidiary theme, and although this is treated at a relatively simple level, it still necessitated considerable research into 'human' geography, and it is felt to be of great potential importance, not least because by including human features one can attempt to synthesise 'realistic' maps. As this is not physical geography some of the references are invoked in the appropriate chapter (chapter eight), and not necessarily in the chapter which is dedicated to previous work (chapter two). Each chapter is discussed individually below.

1.1 Summary of the chapters in this thesis

Chapter one identifies the reasons for undertaking the research. It asks the question: *'why synthesise terrain?'* and also attempts to give some background information to the study. The chapter points out that although physical geography occupies most of the effort involved in the research, there are several overlapping disciplines or technologies that had to be combined in order to produce sophisticated synthesised terrain models. These disciplines or topics included human geography, Geographical Information Systems (GIS), Information Technology (IT) and other earth science and social science disciplines such as geology, hydrology, settlement geography, cartography etc.

Chapter two is a review of previous and related work, and comprises an examination of literature concerning the major themes that make up the thesis. This chapter, therefore, reviews (through the literature) the multidisciplinary approach to the work, taking a particular stance at examining **military** and **non-military** work. Much ground is covered, since the particular area of digital terrain modelling under study requires an understanding of different fields within the earth and life sciences, as well as computing and mathematics. First, as the field of 'geomorphologically-initiated' synthesised terrain literature *per se* is painfully sparse, terrain modelling is examined in itself, since synthesised terrain models (and ultimately synthesised maps) - are what the research sought to acquire. Indeed the synthesised terrain models are stored and presented in much the same way - and using the same formats - as 'real world' digital terrain models. This is followed by a rigorous but <u>selective</u> review of geomorphology theory and practice, as well as a brief look at those areas of earth and life sciences of relevance to the thesis, principally hydrology and geology.

This multidisciplinary approach also explains why the review should also concern itself with various associated applications, such as the development of terrain modelling generally for civil and military reasons. Also, the development of world wide Information Technology (IT), where relevant, is also examined briefly, as it is this - by definition - that has made computer modelling, database storage and visualisation of terrain, and the related geographical information systems or related technologies possible. It is not considered practical to produce a thorough review of the development of IT over the last 30 years - indeed that would take a thesis in itself - so only the relevant areas are identified and described. However, some IT-related information is reviewed in chapter two, which also gives a structured outline of the principal themes of interest and the main players within those themes.

Finally, although the chapter is devoted to the dual military and non-military backgrounds, there is some information provided about other attempts to create synthesised terrain, including the genre of science fiction, the motion picture industry and hardware models. Some World-wide web (WWW) sites are also examined for the sake of completeness.

Chapter three looks at the methods used in the research to create synthesised terrain. This covers physical terrain (surfaces, mountains, rivers, slopes etc.) although some 'human geography' is mentioned, even though this is covered as a separate theme in Chapter 8. Chapter three goes on to review, compare and discuss the various methods of synthesising terrain, and compares these briefly with the methods of collecting real data, such as photogrammetry. The concepts of scale, resolution, accuracy, and the application of terrain classification are utilised. Also, the concepts involved in 'initialising' the synthetic terrain by means of a 'primary surface' or 'trend surface' are reviewed.

By far the most important function of this chapter is to produce a number of 'working hypotheses' that can be used to produce code and software packages. The most sophisticated area of research has led to a software program (or more correctly - a suite of programs) known as ***Geoforma***. It is Geoforma that represents the pinnacle of all the research in that - 'warts and all' - it reflects the best practices and optimum approach to creating synthesised terrain under the conditions by which the specifications for such models were demanded.

The next four chapters each apply the methods described in chapter three alongside selected software and/or Geoforma (e.g. as a composite method) to produce particular types of landscape. Where appropriate, algorithms are customised to produce desired effects, as required by the 'end user' or 'sponsor' (defined either as the author or as the agency and/or persons who required the synthesised terrain data sets at certain points during the research).

In particular, the diverse methods of creating 'digital synthetic landscapes' are examined in more detail, together with the geomorphological inputs that are felt to make the difference between 'end-product' terrain that is simply 'fantasised' through mathematical modelling, and terrain that is created to demonstrate a measure of realism by accessing 'real-world' attributes. Indeed a thread running through the entire thesis is the constant striving towards geomorphologically-viable terrain (indeed 'geographically-viable' terrain where human geography is concerned), or - in some cases - synthesised terrain that mirrors a particular type of scenery or locality. This in turn led to the need for putting resources into two important facets of the research:

- Modelling landforms and geomorphological environments (coastal areas, deserts, uplands, fluvial scenery etc.)

- Modelling chosen geographical areas - otherwise known as physiography or 'regional geography' by means of techniques borrowed from the field of terrain evaluation (including parametric analysis).

To express this dual concept another way, consider the following: the real world has been examined from two perspectives; first from the point of view of landscape type, as in a generic geomorphological 'example' of landform assemblages (such as a 'text-book' drainage basin or a drumlin field), and secondly, from the point of view of physiographic region - as in a specified part of the world such as 'The North Downs', 'The Weald' or 'The North German Plain'. The methods will naturally vary with scale, resolution and the desired 'deliverable' or end-product.

It has been found that the two types can be combined, within reason, and the difficulties (and advantages) of modelling composite landscapes are discussed. It might, for example, be unrealistic, inappropriate - perhaps even absurd - to model recently-formed glacial features in what is today a tropical region (although continental drift and other mechanisms must make one wary of such sweeping statements), whereas drainage is virtually universal, and a drainage basin can be 'emplaced' in almost any part of the world apart from the polar regions. The point is that the selection process for the areas concerned was constrained by both common sense and, to some extent, by the requirements of the research sponsors. The importance and validity of introducing real-world parameters derived from actual maps is discussed, along with the philosophical aspects of whether this is still 'synthetic' terrain or merely a twisted derivation of some real area.

Since computer modelling is used extensively, the user has been given (in circumstances where Geoforma is available) the facility to 'edit' or modify the synthesised terrain to produce a particular end result. Again, the impact on the 'geomorphological viability' of such undertakings is examined, although most of the philosophical discussion about synthesised terrain *versus* real terrain is confined to a dedicated chapter (see the description of chapter 9 below).

Chapter four examines the application of the research to model stream features (fluvial landforms) and drainage basins, ranging from relatively primitive methods used by the author in the late 1980s to more enlightened examples, some of which are produced from work associated with, or derived from established research which led up to the most sophisticated versions of the software known as Geoforma.

Chapter five continues this theme with the modelling of mountainous or upland areas, particularly using the mathematical concept of fractals and 'super-ellipsoids' to model upland structures. The use of geological factors and their impact upon a synthesised surface is interesting, as several options were available (this is a theme that occurs in other chapters too). The first option is to ignore geology altogether. Secondly, geology can be incorporated and used in some simple form to explain polygenetic landforms (like 'hard rocks' and 'soft rocks' and their relative effect on erosion). Thirdly, the theoretical effects of geology can be 'rationalised' in some way to explain the resultant topography after the terrain surface has been created (e.g. by linking upland areas to harder lithologies). However, this is felt to be a somewhat undesirable approach as it is not really using geological effects in any scientific and useful way, but seeks to rationalise them in retrospect - hardly a rigorous method. Whatever the option, this somewhat difficult philosophical situation is critically examined in this (and later) chapters.

Chapter six continues the upland and river landscape theme, but attempts to apply it to the granite area of South West England, where the author has an intimate knowledge (through fieldwork) of the granite and upland scenery and is in possession of a collection of maps and photographs (Griffin 1977). This exercise was also intended to research the applicability of different scales and resolution, so three scales of terrain - from trend surfaces down to large-scale map features like tors - are examined. This is the only part of the thesis where 'micro-terrain' is synthesised, as part of the exercise. Also, it was felt to be desirable to apply the hard-won techniques and methods to geological structures in a real area, even if the models are only relatively simple. The results are analysed and discussed.

Chapter seven enlarges on the concepts introduced in the previous chapters to produce coastal scenery, and provides models, with a brief discussion of the theoretical advantages and disadvantages, as well as some examples.

Chapter eight examines how the synthesised terrain concepts can overlay human geography attributes or features - known for convenience in this thesis as 'infrastructures'. These attributes include roads, railways, settlements and woodland - which are overlaid on a physical landscape to make relatively realistic and impressive maps when plotted as 2D presentations. However the maps are somewhat of a paradox - for 'true' synthesised terrain complete with maps, place names, woodland and other features tends to stretch the imagination somewhat.

Place names - for example - are also synthesised - even though it is acknowledged that place names are derived from a vastly complex cultural melange involving linguistic, socio-economic, historical and many other factors - to produce a synthesised place name model is really only to help make maps more 'realistic'. The author's research led directly into the formation of requirements (by an MOD sponsor) which indirectly affected the research because it requested a place name synthesis algorithm. This was done therefore to satisfy a requirement rather than attempt to provide a generic model. All the same, such work was interesting and this is one of the areas identified for future work.

Yet despite the obvious dangers of straying from the main theme of the (mostly geomorphologically-based) research, it is worth at least identifying the human geography problems involving synthesised terrain cartography that have been encountered in 'live' projects. The human geography work was done because a synthesised terrain map is not really complete without some 'true' topographic details - such as roads, railways and settlements - this is the ultimate expression of synthesised terrain - it is not just mountains and rivers. Clearly this research area could generate an entire research project in itself. It is freely acknowledged that the chapter is no more than a starting point; it is hoped that the work done will inspire others to examine the possibilities and move this fascinating area forward; it represents an area of potential future work.

Chapter nine examines the all-important area of validation and attempts to address some of the philosophical problems that have arisen during over the years of research into synthesised terrain. It poses the question 'how may one validate terrain that has been synthesised?' and it also attempts to identify (and supply) reasonable answers. The effects of manual intervention (by means of 'editing' topography) are also identified and reviewed, and various 'acceptance criteria' are identified and discussed in terms of the classes and types of artificial landscapes required. This chapter also examines the 'value' of synthesised terrain - indeed it addresses what might be termed the 'overall viability'. This leads to how and why synthesised terrain can be used to create maps and other visualisations instead of utilising real maps and 'real world' terrain information systems. Indeed the chapter attempts to probe the relative 'value' of the terrain - what is useful and viable to a military planner may not - for example - be acceptable to a geomorphologist or hydrologist, and indeed *vice versa.*

There then follows a more general discussion, which is both a comparison and contrast between maps of real landscapes and those based on synthesised terrain from 'real' areas (from deliberately chosen physiographic origins) and terrain that has been modelled purely 'synthetically' - without reference to real maps. Clearly there might be a paradox here; if one uses a map of Germany to create entirely fictitious but geomorphologically-viable 'German' landscapes, then to what extent is this model really synthesised terrain? Is it only a distorted reflection of the landscape, or an ingenious method of gathering a detailed DTM where no data existed before except the 'bare outlines of topography on a map? Such questions are faced in chapter nine.

Chapter ten is a conclusion to the thesis. This chapter discusses the whole area of synthesised terrain in terms of a summary of its usefulness, acceptability and possible future development. The chapter provides some conclusions as well as posing (and attempting to answer) some of the inevitable 'open questions' that may prompt further investigation into the field. It briefly summarises the perceived successes and failures of the research; the real value of synthesised terrain. It goes on to suggest some possible areas of future research.

1.2 Aims and objectives of thesis: the goals

This section lays out the aims and objectives of the thesis.

1.2.1 Overview

This thesis deals with the creation, use and presentation of 'artificial' or 'synthetic' terrain - that is, the production of seemingly real terrain landscapes by means of computer modelling, following careful analysis and interpretation. The thesis seeks to explain why synthesised terrain can be useful in a variety of applications in place of real terrain models, and goes on to elaborate the details of how such synthesised terrain may be created, modified, managed, presented, used, validated and augmented.

The term "synthesis" is described by Chambers Dictionary (1998) as: ***'...artificially produced but of similar nature to . . . not a mere substitute for . .'***. In this thesis the terms "artificial" and "synthesised" have come to have the same meaning. Other terms, such as "terrain", "topology" and "topography" are described and defined below. The driving force behind this work is the desire to create 'accurate' or 'geomorphologically-sensible' terrain that could be substituted - indeed one might ideally say 'mistaken' - for real landscapes. First, one must ask the question: ***why synthesise terrain?***

It is not sufficient simply to state that there are valid requirements for wishing to create artificial terrain, intriguing and interesting though this exercise may be. The history of synthesised terrain, as far as the author is concerned, has been to produce deliberately synthesised (and therefore cheap and rapid) DEMs and DTMs for a number of customers or sponsors in an industrial, military or commercial environment over the last 21 years. The research grew from here; the simple sine-wave 'eggbox' surfaces that can be generated to provide 'backgrounds' for arcade games, industrial landscaping projects or military simulations became insufficiently 'realistic' for the purposes for which they were used - like vehicle movement simulation. The sponsors therefore formally requested ways in which the terrain could be made more realistic. This coincided with private research of the author, and so initially some 'random' landscapes were generated from groups of mathematical functions. Later fractals were examined, and although the resultant landscapes became more interesting, it was clear that 'realism' would have to be introduced in some other way. Moreover, it became clear that providing more realism needed careful terms of reference, and would be a non-trivial task in itself. This led to better and more rigorous models (Griffin 1987) and eventually to research involving sophisticated synthesised terrain models and the ultimate goal: geomorphologically-viable and realistic maps showing synthesised topography (physical landscape and 'culture'). The path of the author's research into synthesised terrain, with the relationship to the improving IT resources, is shown diagramatically in Figure 1.1.

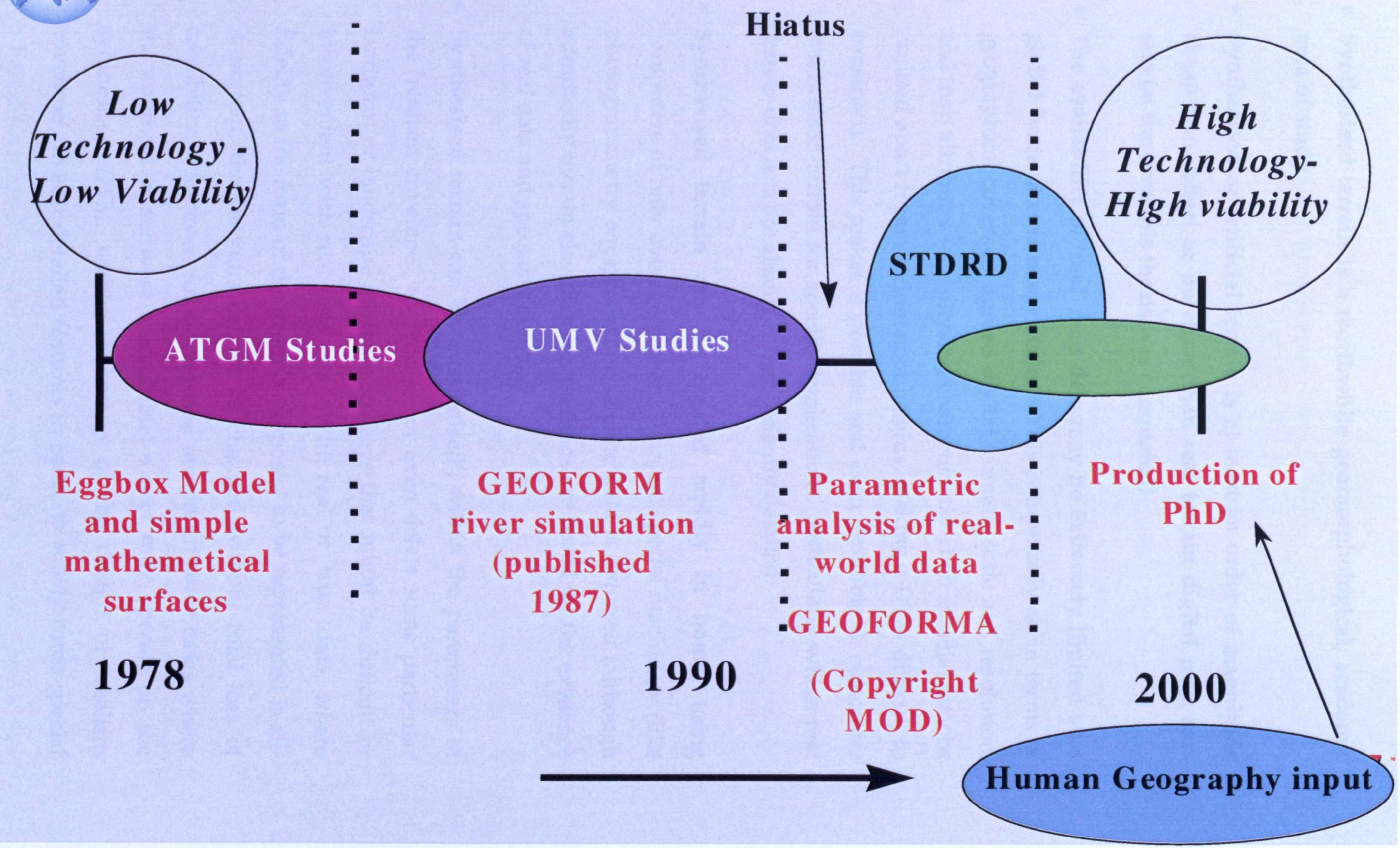
Clearly, apart from the practical problems of synthesising terrain, there are severe conceptual and philosophical problems involved. First, why would one wish to create artificial terrain? This is addressed in the paragraphs below.

1.2.2 Why synthesise terrain?

The justification behind wishing to create artificial yet realistic landscapes, rather than simply use real data, has been mentioned in outline. The work stems from a number of geomorphological and military projects which are referenced in the diagram (Figure 1.1). The projects themselves are described in detail in chapter 2.

Synthesised or artificial terrain is of interest to a variety of academic and technology 'knowledge' workers: it is a valid subject of research in its own right and in this sense needs no more justification than that. However, there were, inevitably, also some practical or commercial reasons that prompted the research thesis, and some of these were based on military or commercial work undertaken by the author. Taken together, all the reasons for creating synthesised terrain can be summarised as follows into broad areas; the principal points of which can be identified as follows:

Fig. 1.1 Progress of private research into synthesised terrain from 1978 to 2000



- **Synthesised terrain is a worthwhile geomorphological, academic area of study**

- **Synthesised or artificial terrain is at least an order of magnitude cheaper to collect or purchase than real terrain digital map data sets (at the time this thesis was completed)**

- **The availability of 'real' map data may be extremely limited on a global basis, across many scales.** This is especially so in terms of geographical coverage, agreed digital formats, scale and resolution, and map attributes (e.g. physical characteristics such as relief may be omitted apart from random spot heights, making a DTM difficult to construct). This makes it possible and even desirable to customise synthesised terrain for specific applications, particularly where real terrain data sets are absent or insufficiently detailed.

- **Synthesised terrain can be created rapidly in hours:** using computers of only average power. Also, no special machinery (like photogrammetry equipment) or satellite data is required (although admittedly terrain classification methods are based on the existence of real data and specialist maps).

- **Synthesised terrain can be 'customised'**, within the parameters of the 'realism envelope', to produce or even delete some particular landform or landscape attribute in ways that might be difficult or inconvenient with real data sets. With real or 'true' data, where fidelity to the form of the ground supposed to be represented is all-important, the contours cannot be changed without total loss of credibility. However, for synthesised terrain (in some cases where the appropriate software is available) a user may operate on the synthesised DTM, within the scope of the design or 'realism envelope', to edit detailed features in order to satisfy some special requirement or effect, without losing the perceived geomorphological 'integrity'.

- **Synthesised terrain may be based on real world physiography.** Using terrain classification techniques on a 'dial up' basis, terrain from areas of enemy or unapproachable terrain may be modelled providing terrain classification exercises (e.g. parametric analysis) have been undertaken first. For example, the army may wish to carry out simulations concerning an area of hostile or enemy terrain denied to them with respect to aerial surveys, photogrammetry or ground survey, but a good approximation of the type of terrain may still be synthesised as long as some maps exist to indicate the terrain 'type'.

- **Sometimes real data simply isn't required.** When a new flight simulator is built it may - for example - be tested against a dummy data set before real (and expensive data sets) are purchased. In other cases - certain British Army training programme among them - the requirement was only for 'realistic seeming' terrain. Some arcade games have similar requirements although geomorphological integrity is hardly felt to be of much importance in most of these.

- **Finally, synthesised terrain may be used as a research or educational tool in its own right.** It may be used to model landscaping projects or help with impact analyses on major civil engineering projects such as dams, flooding valleys, urbanisation, and mineral extraction. Synthesised terrain may even be used to help planetary geomorphologists to build and test models of landform genesis on bodies in our solar system, given coarse or sparse 'fly-by' satellite data.

So there are many answers to the question 'why synthesise terrain?', but the primary drivers to the work underlying this thesis are twofold:

academic interest and availability (and - because of this - cost); real Digital Terrain Models can be vastly expensive, and in some cases a 'realistic' substitute is equally useful or valid. This situation is no doubt improving as satellite information (e.g. Ikonos data sets or Lidar - Light Ranging and Detection - technology) becomes increasingly available, but the subject of cost, convenience and availability of obtaining data sets from remote or hostile areas remains problematic.

1.2.3 Starting points

Another question is this: *from what starting point can the data sets be created?* This poses the question of a 'primitive' surface - and this thesis considers several possible options for this. Merely copying actual terrain is not true terrain synthesis, but is simply manipulating what is already there. Or can 'templates' of real terrain - generalisations of different climatic or geological areas - be used with justification? Indeed, one question poses another, and the need for a primitive or primary surface is a theme that runs through the research.

1.2.4 Validation

There is an excruciatingly difficult question: how can such terrain synthesis be validated? There are no *de jure* benchmarks, criteria or milestones against which the finished article can be matched, since terrain synthesis is a subject in its infancy as far as geomorphological realism is concerned. Indeed there are very few examples - if any - of geomorphologically-sensible synthesised terrain - possible exceptions here include a few contrived specially either for academic reasons, or to satisfy a set of actual requirements - in a landscape modelling project, for example, where an area is to be restored or reclaimed and an 'artists impression' is necessary.

In spite of this, questions abound in every area of terrain synthesis, and yet the cost savings were so important to the various sponsors involved, that a series of increasingly sophisticated projects were carried out by the author over the years with the very aim of creating 'geomorphological viable' scenery.

1.2.5 Other Questions

Even if such scenery can be created - how can it be presented? Should it be manipulated prior to final presentation? For example, when a synthesised terrain model has been produced and pronounced 'realistic' by whatever criterion set is in use, how far may one 'edit' or change this landscape without losing the perceived integrity or realism? Should manual editing be encouraged or discouraged? Why cannot one use simple mathematical models or fractals - why go to all the trouble of producing 'geomorphologically sensible' terrain models at all? Such questions are addressed as carefully as possible in this thesis, and it is important to understand that they are not merely academic musings, but deliberate goals and objectives in some cases prompted by organisations such as the UK MOD.

Indeed, whereas the author owes a debt of gratitude to the MOD, and to other commercial 'customers', for sponsoring such work and for allowing the results to be described in this thesis, this also produced constraints. Typically several projects are described as they happened, and not perhaps as geomorphological research techniques would have preferred to direct them. This is the price for undertaking such work - this thesis does not pretend to be the perfect roadmap to producing synthesised terrain for geomorphologically-viable reasons - it simply describes the 'highs and lows' of many years of constrained research, where sometimes - regrettably - cost-effective targets and not geomorphological excellence were the goals (this, incidentally, explains why some school or undergraduate text books were used to underpin algorithms).

1.2.6 Synthesised terrain: Overview

As suggested above, it is felt that there are two main reasons for seeking to synthesise terrain, both of which are based on experiences related to previous work and to the on-going, private work already set in train by the author in the late 1970s. The first is to examine some aspect of the geomorphology of terrain synthesis (process or form), and could be labelled as 'academic' reasons. The second, general set of motives is involved with supplying an accurate alternative to the expensive methods of collecting and constructing detailed DTMs or DEMs by the conventional mechanics of cartography, such as surveying and photogrammetry. These (the second set of) motives might be labelled 'economic' or business-oriented reasons, since synthesised terrain can be an order of magnitude cheaper to construct, with significant gains in the life-cycle (i.e. reduction of 'time-to-market' is a valuable goal for any commercial project). Conceivably the two could overlap - there is no reason why academic research should not benefit from the reduced cost of synthesised terrain if real world areas are not specifically required to teach, for example, the principles of landform morphology and process. Another example could be a GIS system used for training students in general navigation, or some aspect of cartography, where digital data is required at a large scale (say 1:10,000), but is either not available or is too expensive to obtain. In this case *real-world* data may not be required at all and could be replaced quite satisfactorily with synthesised terrain data sets as long as they were subjectively (and perhaps statistically) 'realistic'.

1.3 Digital Terrain Models

A short introduction to the principles of digital terrain modelling is necessary, as the synthesised terrain data is treated in exactly the same way as real data sets, using the same data formats, structures, processing techniques and GIS systems. Therefore some discussion -

with references - is given in Chapter two so that the scene can be set for the techniques by which DTMs and DEMs are normally acquired and managed.

Drawbacks are obvious - to be treated as digital models the synthesised terrain must be within agreed bounds of accuracy and geomorphological realism to be counted as a high-fidelity landscape, and manual screen edits (to real or synthetic terrain) must also satisfy these conditions. Moreover, there are cases (such as military operations) where clearly there can be no substitute for real-world maps. Validation is the main condition that must be satisfied if synthesised terrain is to be accepted for such applications; this is a major topic that is explored in detail in this thesis, as it is key to the whole concept of 'geomorphologically-viable' DEMs.

1.4 Originality of this work and contribution to other disciplines

The relationships of this work with other fields must be judged accordingly, as it is not the purpose of this thesis to evaluate the usefulness of synthesised terrain apart from within the scope of the areas defined in the study, such as geomorphology. However, it is suggested that a statement of the key topics and issues involved with terrain synthesis may have some value to workers in the following areas:

- Terrain Modelling and Surveying
- Other earth sciences (hydrology, oceanography etc.)
- GIS and other landscape visualisation techniques
- Teaching and training aids
- Navigation (e.g. airborne and marine equipment testing and simulation)

- Cartography (e.g. data sets for testing of plotting equipment)
- Environmental planning (impact of proposed landscaping mining or gravel extraction areas etc.)
- Entertainment industry (arcade games, audio-visual effects etc.)
- Other (e.g. military simulations, military training, graphic design, art etc.)

In fact, some of the topics listed above have had a direct input to, and influence on, the subject of this thesis. The reason for this range of possible applications is the ability to create, rapidly and at any reasonable scale, DEMs or DTMs that are potentially 'representative' of landscapes found in almost any climatic, environmental or geographical zone, with customisation of features (within limits) allowed as an added attraction. Such DTMs are also designed to be relatively realistic on both subjective and statistical grounds, as opposed to mere 'fantasy' landscapes - however spectacular - that one might produce from the manipulation of, say, fractals alone.

It is suggested that this was, until recently, an almost inconceivably difficult area of research, and that 'sensible' artificial landscapes are only just beginning to realise their potential when compared with the expensive and time-consuming collection of real data sets. The point is this: that sometimes it is vital to deal with actual, existing tracts of land, as in innumerable examples where humans interact with the real world, such as real-time navigation for aircraft or vehicles. On the other hand, there are instances where it does not matter that the landscape is not real, as long as it 'could' have been real, it could have been based on real world terrain evaluation, or that it is realistic according to the requirements of the end-user. A good example is the use of training simulations where a projected 3D background is used for vehicle or flight simulations.

At the risk of labouring the point, in many cases, it simply does not matter if the terrain is real, as long as it obeys the basic principles one might expect from real terrain. One may therefore postulate a 'continuum' of realism for synthetic terrain, usually based on a set of criteria, ranging from obviously contrived and 'artificial' at one extreme to so-called high-fidelity or geomorphologically-viable landscapes at the other.

This can be refined so that these principles echo or reflect the attributes of terrain associated with a particular region or area to an extraordinary degree: in one case, at a training establishment in the UK during 1996, a simulation user actually insisted that the background map presented to him was an area he knew personally in central Germany, where indeed the 'primitives' for this particular example were derived. The difference between 'high-fidelity' terrain and mere 'copying' is very fine indeed in some cases, as will be discussed in the chapter on validation (Chapter 9).

The scope of the work is mostly (but not exclusively) confined to the 'natural form of the land'; this is the 'bare' topography without buildings, settlements, communications or other aspects of human habitation - in other words 'terrain' as defined by Petrie and Kennie (1990). Strictly speaking, the dictionary definition of 'topography' includes the vegetation, man-made features and so-on found in the landscape (which are sometimes known collectively as 'culture'). However this thesis also uses the term 'terrain' (see 2.3).

The concepts involved in modelling such features are suggested in outline, as are those which cover the modelling of vegetation and landscape attributes (such as colour, texture, soil type, geology, mobility, reflectivity and so-on). This is because, for example, such features or attributes may become operators on the form of the ground, in that the removal of forests may speed up erosion to a catastrophic point, for example. Apart from this interesting sub-theme, this thesis lies within the disciplines described by the terms geomorphology and computer modelling, with references to mathematics and terrain classification or evaluation made as necessary.

1.5 Conclusions of this chapter

No doubt claiming that 'one is only following orders' is sometimes used as a justification for many unscientific or geomorphologically unacceptable activities. But this cannot be regarded as an honourable escape route for an academic; to claim that ***'the synthesised terrain is valid because the user says it is, and paid for it accordingly'*** is valid, but it is also dodging the issue.

This thesis attempts to rectify this misconception even though the research is a 'long haul' and is prone to some painful compromises; the research that underpinned the various synthesised terrain models explored in this thesis was ongoing and part of the author's area of interest long before any of the official synthesised terrain projects were initiated. Therefore the author adapted - one might say subverted - his private research into official outlets; this was a convenient and 'symbiotic' arrangement as the author was allowed to continue with the research, albeit in a constrained manner and in a non-academic environment; whereas the 'sponsor' received the benefits of an IT-trained geomorphologist, who was leading a team of programmers, mathematicians and other assistants. This arrangement was hardly ideal but it allowed the research into geomorphologically-viable synthesised terrain to continue, and explored new avenues where synthesised terrain models were urgently required (as opposed to being of mild interest).

Ironically, given the skills transfer programme mentioned in chapter two (whereby army clerks had to gain a basic understanding of how to create terrain using Geoforma), in the final analysis it was perhaps inevitable that it was the author who had the most to learn. By 'subverting' the research to produce DTMs 'on demand' many lessons were learnt over the years, and a not unnatural (if unintentional) arrogance about being the only 'geomorphological expert on the project' was gradually transmuted first through denial, but then to a new understanding of the mechanics of synthesised terrain, and perhaps new insights into geomorphology itself. This was a humbling experience but, like many such encounters, the author is better for having endured it, and in retrospect grateful for having encountered so many lively minds and so many innocent questions. *'Why do we have to have erosional models?'* , *'Why can't we use theory X instead of theory Y?'* are questions that produced lively debates, leading to a degree of self-examination and humility, and an eventual acceptance of something that - if not the truth - is at least an honest attempt to achieve the truth.

No geomorphologist can know everything about his or her subject. For example, one of the 'thunderbolts' that struck the author during the course of the work was that the author's cherished geomorphological process-response models (Griffin 1987) - far from being the genesis of all synthesised terrain - turned out to be just a part of a phased, composite approach. Indeed, the process models refined the primitive surface rather than (as was first thought) created it. In retrospect this was painful, but necessary. Two main approaches were adopted therefore: the fractal/mathematical/parametric approach that allows either generic landforms or 'dial-up' physiographic areas of the world to be simulated, and the process-response/manual adjustment models that were used to refine the resultant DTMs to a level of 'super realism'.

From an academic point of view this thesis is about discovery; it is a record of skimming the surface of geomorphology and occasionally diving down into almost inconceivable technical complexity in order to produce what appear to be relatively simple models of convincing and geomorphological-viable terrain; this is indeed a journey of discovery in itself. The output in most cases is simply a map or a 3D perspective view based on a Digital Terrain Elevation Data (DTED) DTM, totally belying the years of research that went into their making, yet this is as it should be.

Therefore the author makes no excuses; what was done is now past; but it was done in the best interests of the research and (where relevant) of the 'client' of the time, and it is hoped that geomorphological integrity, scientific knowledge and the broadening of several horizons has been served along the way.

CHAPTER 2 : BACKGROUND AND A REVIEW OF LITERATURE INTO RELATED WORK

Chapter 2

Background and a review of literature into related work

2.0 OVERVIEW

This chapter reviews the background to the multidisciplinary sciences and technology areas that together contributed to the synthesised terrain research, paying particular attention to the related literature. Each significant area is taken in turn and examined, but the chapter stresses two main areas: the military 'dimension' (as this contributed so much to the development of the author's ideas) and the 'non-military'; by which is meant 'everything else'. Indeed, the pursuit of military studies was one of the paths that provided the author with resources and original requirements to develop the relatively sophisticated synthesis models and Geoforma software that are described in this thesis, so it is paid due attention in spite restrictions placed by military classification and access controls, plus the fact that there are relatively few authors and documented 'works'.

Synthesised terrain modelling is in itself a difficult and relatively unknown area of work, so inevitably there is some overlap of these two divisions (military and non-military) throughout the chapter, and indeed authors cited in this current chapter may be referenced elsewhere in this thesis as it may be desirable to refer to specific papers and works when necessary. An example of this is where terrain evaluation and classification has been described under a military heading, even though landform taxonomies are well known in geomorphology. This was done because the algorithms used were based mainly on behalf of military work.

2.1 Introduction

A 'background and literature' chapter is felt to be necessary in view of the many disciplines involved and in that it helps to 'set the scene'. The research work described in this thesis on synthesised terrain has crossed the boundaries of many subjects - from geology, hydrology, geomorphology, other geosciences and human geography (settlement patterns, transport networks, spatial infrastructures, land use etc.) through to cartography and display techniques. Terrain evaluation and classification methods are important inputs, as are statistics and material gathered from the study of real terrain types. Information Technology (IT) - such as computer-based tools, computer graphics, spatial databases, Geographical Information Systems (GIS), and general computer display and presentation products are also all part of the multidisciplinary approach to synthesised terrain modelling. An important element of the research embraces mathematics (ranging from Fractals and Fourier analysis to simple algebra and statistics) and their application. There is a range of affiliated topics such as military science, simulations, artistic representation and many others, including some surprising sources (such as motion pictures, science fiction etc.). This chapter reviews - as far as is possible without becoming irrelevant - the relationship of these various disciplines to the synthesised terrain research. Although it may sound over-simplistic, this also establishes earth sciences as the most important group of disciplines, with other disciplines acting in a 'supporting role'.

Although 'terrain synthesis' is not really (or at least not yet) a subject in its own right (for example one would be hard pressed to find a text book entitled 'synthesised terrain') there are nevertheless several other important areas where previous workers have contributed to some aspect of this 'composite' topic and terrain synthesis - or artificial landscapes - have resulted.

Within the framework of military and non-military backgrounds, an attempt is made to concentrate on authors who have dealt with terrain modelling and DTMs, those few who have actually manipulated what can be defined as synthesised or artificial terrain in some way (digitally or by other means), workers who have described relevant models in geomorphology and the earth sciences, and finally terrain classification and other related fields.

2.2 Military Systems

2.2.1 General background: Military

It must be stressed that the two decades of research that contributed to this thesis has had support - particularly the recent work carried out for DERA - the Defence Establishment for Research and Analysis - (as part of Ministry of Defence simulation projects) - although it is pointed out that the original research theme belongs solely to the author.

Much of the terrain synthesis work has been part of commercial contracts, where strict terminology is utilised (e.g. 'terms of reference' or TORs, 'deliverables' and 'deadlines' are commonly used phrases), backed up with a legally-binding contract. This commercial atmosphere had mixed blessings; it allowed the author to pursue synthesised terrain research with far greater resources than he could hope to acquire personally, but it also applied constraints and limitations on the research. In consequence, many of the applications for synthesised terrain models were aimed at army simulation and training, as this is useful simply for reasons of cost and accessibility (see bullet points below). In short, synthesised terrain digital data sets cost less than real terrain data sets as long as the application has no (or minimal) dependency on real world attributes. Therefore much of the work is inevitably constrained and - in some cases - enhanced - by the need to provide realistic synthesised terrain as DTMs for the British Army or the UK MOD. This work is unpublished apart from some oblique references (Griffin 1987) but has been going on for many years in several disparate projects - for example:

- The Anti-tank Guided Missile - ATGM - programme at RARDE - now DERA - Fort Halstead, UK, from 1976 to 1982 (itself part of a larger so-called War-game project)
- The autonomous or Unmanned Vehicle (UMV) project at RARDE Chertsey (now DERA) from 1992 to 1998
- The STDRD (Synthetic Terrain Development, Research and Database) army training programme, also based at DERA, Fort Halstead, from 1993 to the 1997.

The author is grateful for permission to mention these unconnected MOD projects, none of which are now classified, but all of which are covered by MOD copyright. (one such project was undertaken at Cranfield in the UK, but no details are known and many such similar projects are 'classified').

Although military uses of terrain synthesis are described separately below, it is worth reviewing one particular area of work as it has direct relevance to this thesis. Quite recently an Army specification (DERA contract ref. : NNR/25b/FY95/96) placed a contract with various UK firms to examine the viability of using synthesised terrain. Some of the original, unpublished material in this thesis was completed by the author while directing the work on this particular contract, with MOD permission. The author used landscape classification techniques to provide the primary surface and the attributes of a particular geographical region (see chapter 3). This was then combined with process-response models (many of the concepts of which were available in earth sciences literature) together with static models of 'primary surfaces' to produce DEMs, which could be edited, displayed or produced as maps. A refinement of the process (which was based on off-the-shelf GIS packages and Geoforma) allowed users to 'augment' real terrain. This meant that users could position their own 'mountains' and view the result. Although this project used much of the author's original research (including the basic algorithm and the name of the program GEOFORM originally written and published by the author - see Griffin 1987) the author is grateful to the UK MOD for allowing him to reproduce some of the diagrams and techniques in this thesis.

Another branch of the work, which does not concern geomorphology directly but instead was influenced indirectly by deterministic principles, was the creation of urban and rural settlements (based on the work of Christaller (1933) and Lösch (1954), among others), as well as the application of nearest-neighbour analysis to determine communication paths (roads, railways, etc.). Vegetation was based on a land-use model, with 'wild' forests being sown on a 'game of life' basis, with proximity to other trees, aspect, slope, drainage etc. all contributing to the growth or demise of woodland, an idea again suggested by the Author's 1987 paper.

The DERA STDRD project as a whole was summarised in 1996 (New Scientist 1996) under the title *'Fantasy landscapes look just like the real thing'*.

2.2.2 Hardware models of the landscape: Military versions

There are other examples of synthesised landscapes by various schools of landscape painting (military or otherwise) throughout history (Royal Academy 1988), or as models, whereby 'hardware' analogues of terrain could be created for a variety of reasons. Unfortunately, such examples are far harder to find in the literature.

One clear use of scale 'hardware models' - if we may refer to these as such - (e.g. clay or plaster of Paris models) was for museum display or training purposes in the military, where synthesised maps or even scale models would be created for various purposes, including the teaching of students the tenets of intervisibility, dead ground and 'live ground' (where intervisibility is possible), according to the military doctrines of the time. Indeed, it has been popular for many centuries for generals to produce scale models of landscapes showing enemy positions. For example, some of the more responsible Allied officers in World War I made careful models of the land they would be attacking over, particularly during the infamous battle of the Somme in 1916 (McDonald 1983, Brown 1998).

Perhaps one of the finest examples of a location of map tables and battlefield or scenario models - where the map is really a beautifully detailed model - is to be found in *Les Invalides* (the French Army Museum in Paris, located near and several floors above Napoleon's Tomb). An entire floor is dedicated to these superbly made terrain models - usually at a scale of 1:600 - sometimes larger (see Figure 2.1 for an example). Interestingly, some of the very large scale forts, at about 1:500 scale, have 'synthesised terrain' surroundings, since they are surrounded by marsh or swamps that - not surprisingly - no modeller has seen fit to survey. This is hardly synthesised terrain but it shows how useful imaginary terrain can be for 'filling in the gaps' (there is no apparent reference work in any language except for a

Figure 2.1 Scale Model of Military Terrain (from *Les invalides* Army Museum, Paris).

leaflet; for more information see *Musee des Plans-Reliefs, Hotel national des Invalides, 75007 Paris*).

Examples abound in the literature from the lines in the sand drawn by ancient generals to beautifully-constructed scale models made by various Warlords throughout history, some of which still survive. For example, a model landscape surrounding a bridge attacked during D-Day (1944) survives in a museum at the Royal Corps of Signals, Blandford, UK, and there are similar models at many other military establishments and military museums in the World. Another method is the 'sand table' which is described (Forty 1997), as *'a model of an area of ground made from sand with a wooden surround, model buildings etc. Some models will be to approximate scale only, others may be far more detailed and exact'*. Forty (1997) also includes a photograph of a briefing on one of the sieges of Tobruk in 1942 using a sand table (page 189). Sand tables were used extensively throughout World War II and prominent features, such as hills owning tactical importance, were easily presented (Blandford 1999). No doubt sand tables were used to outline theoretical tactics over 'imaginary' terrain as well as being used for real operations (Brigadier A.W. McKinnon OBE - a veteran of the Korean War who is aware of the author's synthesised terrain work - has kindly written to the author to confirm this point).

Even the Persians, Greeks and Romans and other peoples of antiquity are thought to have made models of terrain for their generals to demonstrate theoretical tactics and although unfortunately there are apparently no direct references to such models, there are several references to the effect of terrain on various campaigns (see for example Plutarch: *The Age of Alexander*). The Assyrians had relief 'maps' of various areas, including one from Sennacherib's palace showing the salient features of a military camp from around 700 BC (Bowker 1998). Naturally many ancient maps and models were 'training aids' that in turn were attempts to copy real areas, and therefore do not qualify as synthesised terrain in any sense of the term. Yet it is only a short step from modelling real ground to creating 'typical' or 'representative' ground to demonstrate a point. Indeed, one can only speculate as to whether imaginary models were constructed to teach students the military benefits of dead ground, defensible positions and similar theoretical military aspects of the landscape that have been in soldiers manuals through the Ages, since none have survived, although there are some allusions. Indeed Cartledge (1998) discusses the 'first geographers' - such as the Greek Hecataeus and his maps from the Greece of the mid-fifth century BC.

2.2.3 Terrain Synthesis for Military Work

Maps and terrain have always been of paramount importance to the military mind (Goodenough 1982), and the same can be said of any development that portrays terrain for military applications, such as DTMs. When the military authorities could not get accurate DTMs, they considered synthesised terrain, as is described below.

'True' synthesised terrain, therefore, appears to have been developed in tandem with Information Technology; it has already been mentioned that the computer revolution starting from the late 1970s created the conditions whereby software-based synthesised terrain models could be attempted. Indeed, it is ironic that the reasons for wishing to create synthesised terrain, outside academic study, were also spawned by the same computer technology which contributed so much to producing real terrain. A good example is the work done at the Royal Armament Research and Development Establishment (RARDE) between 1978 and 1981, where anti-tank (AT) mathematical modelling required accurate models of real terrain in so-called threat areas such as Germany (this was at a time when the Cold War was 'raging'). Since digitised data was rare and difficult to manipulate in the slow mainframe computers and poor GUI (Graphical User Interface) media of the time, some of the work used simple mathematical models to simulate terrain over which simulated tanks and ATGM systems could roam in search of targets. The most prolific of these synthesised surfaces was the so-called 'eggbox topography' (Gilmour and Griffin, 1979, 1980a, 1980b), derived from simple sine-wave equations. The resultant 'topography' when viewed in 3-dimensions, appears (with a suitable vertical exaggeration for 'operational' purposes) in Figure 2.2 (a). The equation for the eggbox topography is:

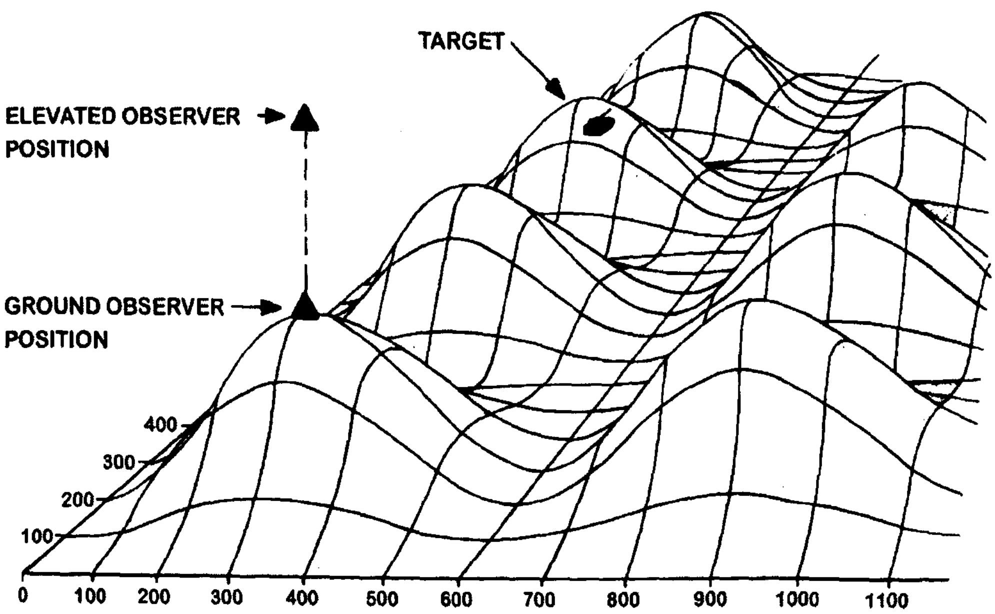
$$\mathbf{z = -a(\sin^2 bx) \cdot (\sin^2 by)}$$

Where a is the relief amplitude (e.g. in this case 200m is used) and b is a scaling factor (values around 0.3 are used in the illustrated example). The minus sign is redundant and is included only because the aeronautical Cartesian axis system assigns all heights above the origin as negative (Blakelock 1965).

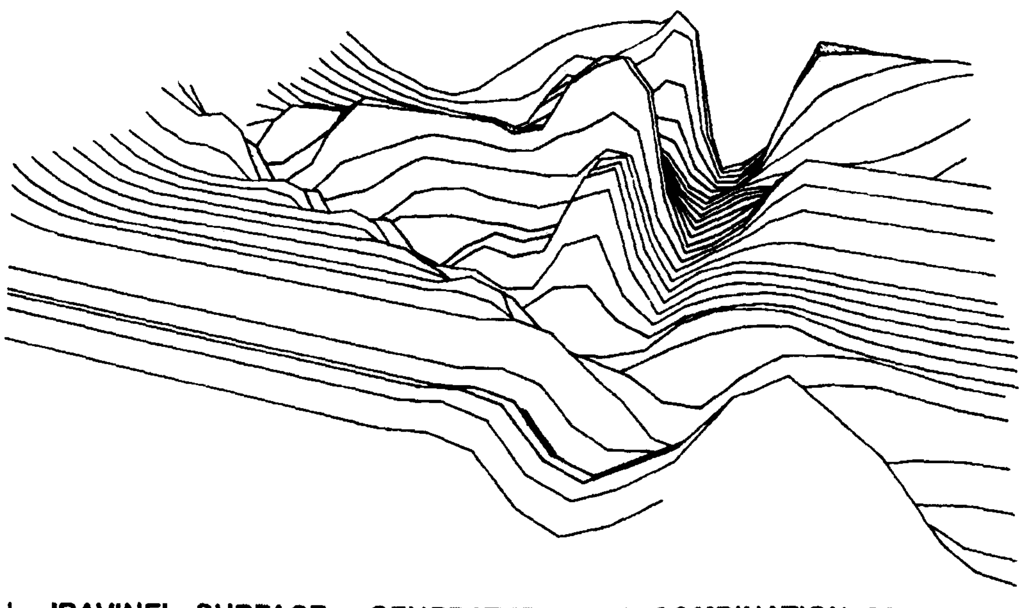
Terrain based on various functions of:

$$\mathbf{z = f(x,y)}$$

are also shown in Figure 2.2 (b) (where **x**, **y** and **z** are Cartesian co-ordinates - see chapter three for an explanation of the utilisation of this 'right-handed' axis set in the research) - but a significant amount of work based on trial and error failed to produce anything more convincing than the 3D picture shown in the figure.



a. SINE WAVE 'EGGBOX' SURFACE USED TO ESTABLISH TARGET - OBSERVER DYNAMICS



b. 'RAVINE' SURFACE GENERATED BY A COMBINATION OF 5 MATHEMATICAL AND STATISTICAL FUNCTIONS

Figure 2.2 Sine Wave 'Eggbox' surface (a) and synthesised ravine (b) (from Griffin 1990).

Interestingly, real terrain is often shown in GIS 3D programs with a deliberate vertical exaggeration, as so many areas of the world are relatively 'flat' (see for example Jenks and Caspall 1967 on this topic). Naturally, this type of 'contrived' terrain was an expedient, without any attempt at realism or emulating the topography over which the British Army would, at that time, be fighting for its life in any war against the (now-defunct) Warsaw Pact. Today such statements seem almost crass, but in 1979 - 1980 the world was close to war between the superpowers - perhaps closer than most people realise (Hackett 1983). The target indicated in Figure 2.2(a) gives a hint as to the purpose of this sort of simulation (in fact it was connected with Anti-Tank (AT) studies).

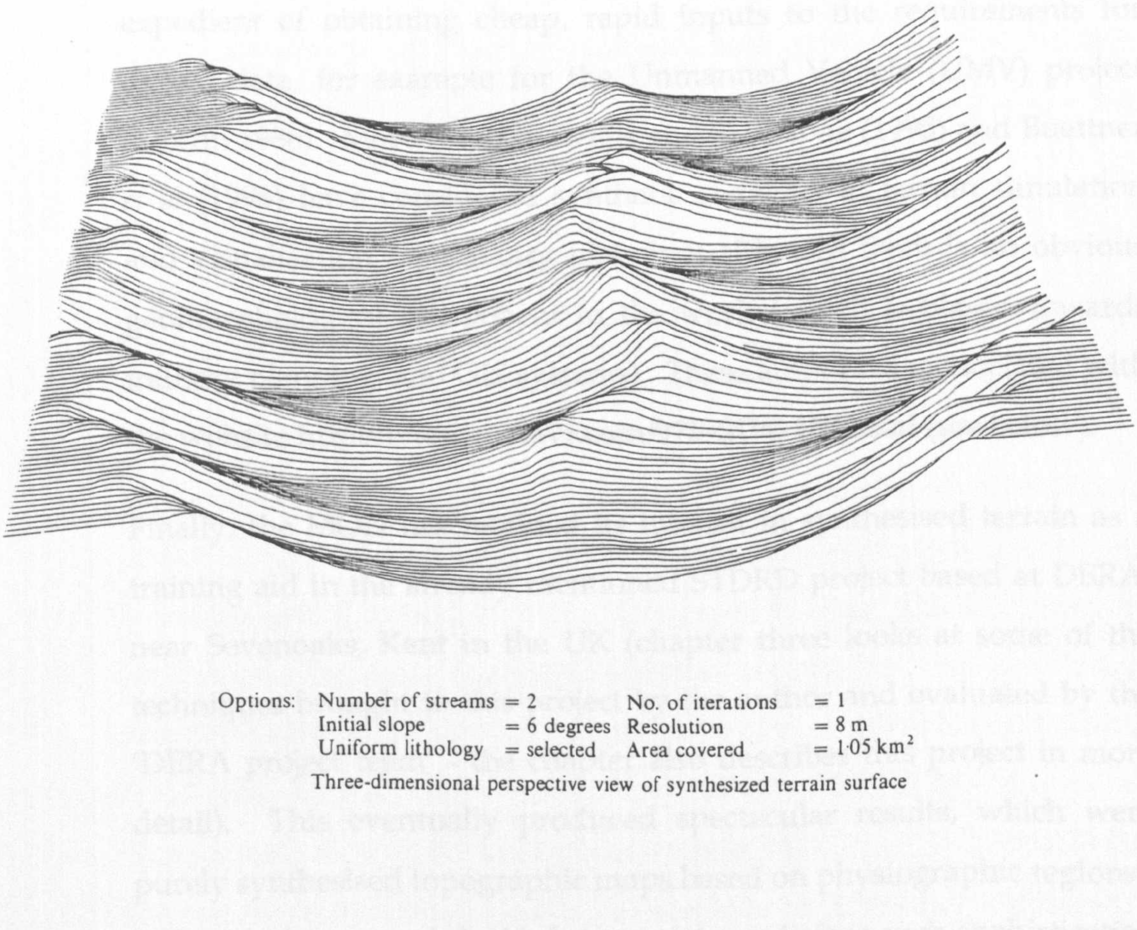
An important side-effect of such modelling was the development of the algorithms and software to 'visualise' the surfaces where battles might take place. Although crude by modern standards, in the days before PCs, when only Oscilloscope-like displays were available for vector-plotting, such 3D views were considered 'state of the art'. Various papers were produced on viewing techniques (Griffin and Gilmour 1981); although such technology applications appear to have been developed simultaneously in several parts of the world, and are now taken for granted as part of standard PC viewing applications in GIS packages.

Other workers in the military field included Tindall *et al* (1986), who examined the usefulness of three-dimensional terrain graphics for the battlefield. The related aerospace field also linked up terrain modelling with remote sensing and satellite imaging (Leberl *et al* 1986, Muller and Saksono 1986). Scholz *et al* (1987) examined the generation of shaded relief in aeronautical charts. Remote sensing is another subject that formed its own following and now generates its own literature and user community (Balce 1987), although much of the aerospace work is by necessity controlled by governments and academic publications can be rare, except where land-use and environmental imaging is concerned. For obvious reasons military work tends not to be published, or is rarely encountered in learned journals. Possible exceptions to this observation included UK Government-funded military work carried out at RARDE Chertsey (currently called DERA at Chertsey) for various so-called 'autonomous vehicle' (robotics) projects. In one such study (in the late 1980s), the details are worth examining more closely. The requirements for very large-scale maps (e.g. scales greater than 1:10,000) and associated digitised map data (DEMs) was not satisfied by 'normal' acquisition, since it required drawing on resources outside MOD thereby making the work prohibitively expensive. This meant in turn either using material from the UK Ordnance Survey, who covered only a limited area of the UK in the form of large-scale digital maps, and which were found to be presented in an incompatible format (as far as this project was concerned), since the digitised maps used vectors or contained no height information at all, apart from sparse random spot heights. The alternative was to fund a private data-collection exercise, involving considerably expensive aerial surveys and photogrammetry to produce data of the necessary quality and type. So a third group of methods was explored, and this involved initially the use of mathematical derivations to produce surfaces necessary for the various simulations needed to test the sensors on the autonomous vehicle (Griffin 1986) for route planning and autonomous navigation. The eggbox algorithm was borrowed from the author's earlier work, but found to be too crude. So instead more subtle combinations of equations were tried on an experimental basis.

The Autonomous Vehicle project, itself well documented at the time (Smith 1986, EASAMS 1986, RARDE (Ch) 1986), found that none of the purely mathematical methods was suitable for simulating or representing the types of 'real' terrain that the MOD scientists required. At this point, the requirement for synthesising terrain became more important than the means through which such terrain could be generated - in other words, as long as the terrain was more 'realistic' than that produced by simple mathematical methods, the MOD scientists were satisfied and the sensor simulations could proceed without the need, the expense and the delay involved in purchasing expensive, real DEMs. Interestingly, other workers were examining alternatives (or additions) to photogrammetry about the same time: for example Kennie and McLaren (1988) presented a paper on simulated terrain DTMs to an audience of remote sensing and photogrammetry experts.

For the Autonomous Vehicle Project the advantages of attempting to synthesise terrain were obvious to all - the control of scale, format and the landscape itself could mean complete independence from the principal and expensive sources of digitised data available at that time (primarily the NATO DLMS - Digital LandMass System - database, and data from mapping organisations such as the UK OS, Huntings Surveys and other sources). Moreover, the landscape could be created to emphasise or to facilitate a particular feature being tested against vehicle 'performance' in the simulation. For example, if the simulated vehicle was to negotiate (simulated) steep slopes then an area of dissected rills and gullies could be 'created' to test the simulated performance under these conditions. A realistic undulating synthesised terrain 3D view (from Griffin 1987) is shown in Figure 2.3.

But there were also problems. After all, how could one begin to create landscapes from nothing without having at least a specification, or some kind of blueprint, template or model? Yet if a template was adopted, would not such a starting point invalidate the objectivity of the synthesised terrain? Also, by what criteria would the resultant landscapes be judged to be 'suitable' or 'realistic'? These questions were not answered at the time of the initial work carried out for military-based projects, as even quite crude terrain was deemed



Options:	Number of streams	= 2	No. of iterations	= 1
	Initial slope	= 6 degrees	Resolution	= 8 m
	Uniform lithology	= selected	Area covered	= 1·05 km^2

Three-dimensional perspective view of synthesized terrain surface

Figure 2.3 Fluvial synthesised terrain (after Griffin 1987)

sufficient to satisfy the autonomous vehicle sensor simulation requirements.

Indeed there is little point in extolling the virtues of synthesised terrain unless it can be shown that most attempts are measurably successful, whatever the grounds for 'success' or for 'failure' may mean. At the time of the early synthesised DEM data sets (the mid 1980s), and for the various MOD projects of the time, these questions were either answered positively by successfully synthesising crude terrain, or more usually they were avoided altogether, by the simple satisfactory expedient of obtaining cheap, rapid inputs to the requirements for digital data, for example for the Unmanned Vehicle (UMV) project (Griffin 1986). More recently Evans and Stanzione (1995) and Buettner *et al* (1996) have considered synthetic elements in terrain simulation and visualisation for military planning, although there is no obvious geomorphological component in the work (which is biased towards military planning and GIS systems). These authors are associated with the website **http://www.metavr.com/97F-SIW-107.html** (see below).

Finally, the MOD has retained its interest in synthesised terrain as a training aid in the already mentioned STDRD project based at DERA, near Sevenoaks, Kent in the UK (chapter three looks at some of the techniques brought to this project by the author and evaluated by the 'DERA project team' - the chapter also describes this project in more detail). This eventually produced spectacular results, which were purely synthesised topographic maps based on physiographic regions - although the research had a long way to go before such sophistication was realised (see figures in chapter 3, 5, 6 and 8)

2.2.4 Cost of producing real world DEMs

The military are possibly the most interested authority as far as using synthesised terrain for cost saving is concerned. Intriguingly, few workers have attempted to establish costs or possible savings, even though cost can be an acute factor in deciding whether to use real or synthesised terrain. Estimates from hydrological surveys in the US in 1992 stated that 2 separate DEMs cost $155 per square mile and $740 per square mile respectively (Wiche and Jenson *et al* 1992). Wiche and Jenson are among the very few workers to attempt to quantify the cost of deriving DEMs from topographic maps. Their figures can be compared with the estimated £10,000 for a single ONC (Operational Navigational Chart) map sheet DEM supplied from UK military sources (classified verbal estimates from aerial survey and photogrammetric commercial sources), and indications that budgets could stretch into millions of pounds to use aerial or satellite surveys to map areas of terrain in nations hostile to the West.

In contrast, synthesised terrain generally costs nothing except the user's time, given that expenditure has been made on a synthesised terrain program and that resources are available. Naturally the cost would vary according to the relative resolution and accuracy at different scales. The examples given above are representative only; it is not suggested that these are universally-applicable cost figures, but even assuming a modest $350 per square mile for DEMs (which by definition discounts 'culture', specific topographic or man-made features), this can be applied to a military TPC (Tactical Pilotage Chart) of 1:500,000 with about 40% sea (Chart TPC D-2C of part of Scandinavia is a good example). In this case there is about 10,000 square miles including islands (please note that this is a deliberately low working estimate only). This would give:

$350 X 10,000 = $3,500,000

This is three and half million dollars for a single TPC - and there are about 10+ overlapping TPCs covering all of Norway, Denmark and Sweden (giving a cost of $35m if a *pro rata* technique or calculation was continued). Clearly, figures of such enormity - and even if we drop an order of magnitude to $0.35m for a single TPC to allow for economies of scale - this is still a huge figure - and it is just for the DEM. If a way could be found to create valid synthesised terrain models with geomorphological integrity, showing realistic and statistically-viable landforms - then providing real terrain is not required (such as for a flight simulator acceptance test) the cost saving would be massive using synthesised terrain DEMs. However, this calculation is for comparative purposes only - it shows only what is possible and does not purport to be an authoritative example of real DEM costs.

2.2.5 Terrain Classification and evaluation

Terrain Classification and evaluation is an area that overlaps military research and non-military earth science work, but it is included in this section on military background as the eventual algorithms (described in chapter three) were based on a composite set of techniques based on work done by the US Army.

In earth sciences generally, several authors have described ways of classifying or organising terrain. This is distinct from simple taxonomies of landforms, as developed and discussed by workers such as Penck (1894), Savigear (1965), Barsch (1969), Kugler (1974) and Speight (1973, 1974). In fact, the classification of landforms appears to have been a relatively unpopular subject, with surprisingly few 'standard' works. The main authorities appear to be the US Army (1956) - particularly the work of the USAEWES (US Army Engineers Waterways Experimental Station) at Vicksburg, the US Army Quartermaster General (the so-called Natick method) and the Canadian Army (Mitchell 1991), and Government agencies responsible for environmental management and land use, such as the Australian CSIRO (see Christian and Stewart 1968), the UK Oxford-MEXE-Cambridge research group (Beckett and Webster 1969), the UK

Transport and Road Research Laboratory (TRRL), and the US Department of Agriculture (USDA). Individual workers have also evolved methods (see Mitchell 1991 for a full bibliography) - most notably the PUCE (Pattern Unit Component Evaluation) described by Aitchinson and Grant (1967, 1968a, 1968b). One should acknowledge that Mitchell (1991) has probably written the 'definitive' textbook on terrain evaluation, although the author found copies of the various US Army so-called 'Natick' and 'Vicksburg' papers. These methods are examined in the chapter on methods (Chapter three).

Speight's (1973, 1974) work was taken into consideration in the eventual decision by the author (and, at times, whatever MOD Project team and contractors were rendering assistance to the author under his guidance) to use a 'best fit' process, mostly based on the Vicksburg method but taking workers like Speight into consideration. The author also sought out, requested and collected the original 'Vicksburg' and 'Natick' US Army report papers before undertaking to use the parametric method. Indeed, the final approach towards building the algorithm in this thesis was the Vicksburg method refined by elements of the 'Natick' system, simply because this approach was relatively easy to turn into an algorithm.

The point of classifying terrain is to attempt to build up 'units' or 'components' of landscapes, thereby making the understanding, management and usage of such land easier. However, terrain classification is not particularly well documented, and few workers in geomorphology seem to be attracted to it. Possibly the immense difficulty of finding 'order' or universal components is one reason - terrain is notoriously difficult to classify and package - even allowing for similarities in geology, latitude and climate.

However, notwithstanding these conceptual difficulties, terrain classification has been found to be a useful starting point for synthesised terrain exercises - far better, for example than a 'blank map sheet' approach. The balance has to be drawn between 'cheating' by using too many real terrain elements in the landscape model, and by compounding an already difficult task by not referring to real terrain at all, except in theory. This 'balancing act' is crucial as far as synthesising terrain is concerned, and it forms a central theme in this thesis. Mitchell (1991) points out that terrain is traditionally seen as 'hierarchical' in nature, and that this is the most widely used system of classification. One example from many (after Tricart 1965 and Haggett *et al* 1965, from Mitchell 1991) follows:

Order	Area (km^2)	G^a Scale value	Example
I	**10^7**	**1.71**	**Australian Continent, humid temperate zone**
II	**10^6**	**2.71**	**American Piedmont, North European Plain**
III	**10^4**	**4.71**	**Lowland Britain, Florida Peninsula**
IV	**10^2**	**6.71**	**Weald (UK), Cape Cod**
V	**10**	**7.71**	**North Downs, Nantucket**
VI	**10^{-2}**	**9.71**	**Terrace, scarp, fan**
VII	**10^{-6}**	**13.71**	**Soil polygon, tussock, runnel**
VIII	**10^{-8}**	**15.71**	**Weathering detail on rock, pebble**

Table 2.1 Scale of landforms

This is where the G factor is a 'scale value, given that the area of the globe is:

Area = (5.098×10^8 km^2), so that:

$$G = 8.7074 - \log R_a \ (km^2)$$

Mitchell points out that most terrain classes of practical significance lie in the middle of the range, and indeed the research undertaken and reported on in this thesis tends to focus on areas of the order IV to VI.

2.2.6 Skills Transfer: the problem of educating non-geomorphological workers in the military sector

One of the most severe problems associated with carrying out exercises across disciplines was the necessity for 'skills-transfer'. This entailed explaining, and to a certain extent - training - non-geomorphologists in the concepts used to produce geomorphologically-viable synthesised terrain. This was done so that the 'users and the sponsors' - i.e. those authorities who had commissioned the work - usually for military simulations - could understand and appreciate the effort that had gone into making the DTMs as realistic as possible, which was one the major requirements in at least two MOD projects.

An analogy would be for a surgeon or a physician to explain, in layman's terms, the outline of a complicated medical operation to a patient. Clearly the information must be imparted, but it also must be somewhat degraded technically in order for the layman to understand it. Moreover this must be done with good will, and without patronisation.

This exercise was carried out several times on behalf of the UK MOD and other authorities. To explain the models, a short guide to geomorphology and terrain classification was produced and communicated in short presentations. Because it is clearly impossible to condense geomorphology into such short 'workshops', the presentations were of necessity short and tended to concentrate on specifics.

Erosion was one particular theme. The Davision model (Davis 1909) was explained, along with Penck's (1953) reservations, as a starting point. Then, concentrating on planation surfaces, simple slope models and some selected example of stream and valley development, the presentation demonstrated how such concepts were backed up by a wealth of considerably more technical and detailed research. This was augmented by more complex ideas such as the dynamic equilibrium theory - (see for example Strahler (1952), Hack (1960), Chorley (1962) and Small (1980)) as a further example of geomorphological development. Some examples were given by means of 'chalking and talking' to the audience, to demonstrate the complexity of geomorphological diversity, and to make the potential user aware that the explanations given were the 'tip of the iceberg', and that geomorphology cannot be learnt in a few days. For this reason some simple undergraduate text book models were utilised as opposed to a deep geomorphological analysis of the subject matter.

2.3 Work in the field of earth sciences

2.3.1 Digital Terrain Models

A short introduction to the principles of digital terrain modelling is necessary, as the synthesised terrain data is treated in exactly the same way as real data sets, using the same formats, structures and GIS systems. Therefore some of the salient points concerning DTMs and terrain modelling generally are apposite to the work. DTM is a term attributed to engineers working at the Massachusetts Institute of Technology (MIT) in the late 1950s (Miller and La Flamme 1958), who defined a DTM as

> *' . . simply a statistical representation of the continuous surface of the ground by a large number*

of selected points with known X,Y and Z co-ordinates in an arbitrary co-ordinate field'.

Other closely related terms are Digital Elevation Model (DEM), Digital Height Model (DHM) and Digital Ground Model (DGM) . Similarly, the word 'terrain' has come to mean *'a tract of country considered with regard to its natural features'* (Kennie and Petrie 1990). Since this thesis is concerned with physical geography, 'terrain' is therefore a good term, although the consideration of 'culture' and man-made features later on in the thesis changes the terminology slightly so that true topographic models are produced.

Formats are also important, although a full treatment of all possible formats is not necessary. Kennie and Petrie (1990) mentioned the DTED (Digital Terrain Elevation Data) format used by the US Defense Mapping Agency (DMA), and indeed the DTED format is one of the ground elevation formats used fairly consistently throughout this research at the request of the UK MOD. DTED, and its feature-related format DFAD (Digital Feature Analysis Data), are part of the DLMS (Digital LandMass System) used by NATO and by many affiliated organisations. Another format used by many (including the author) is to store the only the height values in a file matrix, such that the position in the file defines the X and Y positions. This is a non-standard format but is space efficient, particular in the early 1980s when disk volumes were, by today's standards, very small.

2.3.2 Digital Height Data Sets

The whole subject of creating Digital Terrain Models (DTMs) was developed mainly through the desire to start utilising the power of digital computers to manage repetitive and multiple tasks relating to digital map data. The requirement for managing and storing maps on computers started during the 1970s onwards, and one of the earliest reference to the genre is a paper entitled *Computer programs for mapping* (Experimental Cartography Unit 1971). Other early works include the Display and Analysis of Spatial Data (Davies and McCullagh), produced in 1975, and the work of pioneers such as Sprunt (1970, 1975).

As soon as powerful digital computers were available to users possessing cartographic data, it became possible to represent maps at various scales either by raster (gridded) or vector (linear or string features) data, providing sufficient computer storage and processing power was available, and some means could be found to display or 'plot' the data sets. In addition, data sets that hitherto were merely derived from maps (so-called 'map attribute' data), could be 'processed' in their own right, thereby de-coupling dependence on paper maps. A good example of this is the storage of gridded altitude points, based on a map co-ordinate system, to yield a digital elevation model (DEM). Display software would allow such data sets to be viewed in 3D or in plan, which meant that the user could cause the data sets to be plotted as contours or as views of three-dimensional perspective (the so-called 'cheesecloth' surfaces), at any reasonable scale or vertical exaggeration. Indeed, many systems for visualising digital data have been described (Kennie and McLaren 1988, Petrie 1990, McCullagh 1990), and from the early 1990s onwards (DeMers 2000). It is interesting for the author to have witnessed fundamental pieces of display or manipulation software which initially had to be written 'in-house' become generally part of 'Commercial off-the-shelf' or COTS systems by the early 1990s. This is a case of the same functionality being 'invented' simultaneously at many places around the world. Such multiplicity or 'standardisation' is also probably due to the influence of computer graphics and the resources available to make such code into a 'product' - many of which have become - or are affiliated with - GIS products. Geographical Information Systems are discussed in this thesis together with the general introduction to Information Technology (IT).

Many different methods for storing and representing height data have therefore been suggested, and this is of great value to the management of DTMs. Petrie (1990), while discussing the collection of real world data sets, outlined the methods of grid-based sampling and storage (from squares, rectangles, hexagons and triangles) through to non-gridded data such as contours. Triangulation-based modelling goes back as far as Delauney (1934) and Thiessen polygons, which are used to define geometrically the region of influence of a point on an areal basis (Brassel and Rief 1979, Petrie 1990), are still widely used. Variations on the theme are common (McCullagh 1983) but triangulation and Thiessen polygons - indeed any polygonal storage method - were seldom used in this PhD research apart from for experimental or reference purposes, as they were rarely necessary.

There was, however, a need to use both gridded elevation data and vector (or contour) based data in the current research. In either case the data sets may be complicated by being stored as vectors (strings), or even as random spot heights. The UK Ordnance Survey (OS) utilise both methods for large-scale map data, which is marketed as digital data to supplement or even to produce paper maps (UK Ordnance Survey, 1994). In this case vectors are used in the digital data sets to represent contours and other linear features such as roads, railways, field boundaries and so-on. For very large-scale maps (e.g. 1:5000 and 1:1000) the UK OS display only spot heights, as contours would be inappropriate and clumsy at this level of detail.

It is an interesting principle that contours, which are such a familiar and useful part of any map-literate person's 'toolset', are only viable at certain scales (say, between 1:25,000 to 1:100,000), since it is only on these scales that contours are generally used by the map-makers. At both larger and smaller scales than these, the concept tends to break down, and devices other than contours must be used to represent relief. Fortunately there are other methods of representing height; very small scale maps can use relief colouring to indicate the generalised form of the land, and if properly presented (as in an atlas) this works. Additionally, small-scale maps can also use relief shading or 'relief shadowing' (as if a light source was projected at the map) whereas large-scale maps, as mentioned above, are characterised by spot heights or even 'hachuring' (shading) to indicate very detailed features such as embankments (Peucker 1979, Brassel 1984, Catlow *et al* 1990). However, whereas these are cartographic refinements rather than DTM storage or collection techniques, they are worth mentioning as the output from much of the research has been (apart from DTMs) a map or a 3D perspective view.

It is possible to produce contours from gridded data, and to produce gridded data from regular or random spot heights, and from contours (see for example Peuqurt 1981, Baker *et al* 1981, McCullagh 1983). Naturally some errors will creep in to this process since interpolation or estimation techniques must be used. The algorithm and coding for a contour program (based on gridded spot heights) was written by the author before such software became commonly available - interestingly some of the source code seems to have 'found' its way into various contouring modules (to the author's satisfaction).

It is the experience of the author that gridded (raster or matrix) data is far more convenient to manipulate in digital computers, since it can be easier to process matrices than vectors in some cases. Different storage formats and their relative convenience for manipulation by digital computers is described in detail by McCullagh (1990). Also, it can be easier to map matrices onto pixel maps of high-resolution colour monitors for realistic 2D and 3D views of the landscape, although arguably it is better to represent large-scale maps (e.g. in GIS systems) or contours by vector plotting. This is apparent when one considers that a pixel (picture element) map of a typical raster screen is itself a matrix, with an origin and boundaries. Indeed the principles of the early window-based GUI systems (such as Microsoft Windows 3.1, 95, 2000 etc., and the Xerox GlobalView system) are based on 'mapping' areas of memory onto screen areas, and *vice versa* (Thorell and Smith 1989). It should be pointed out that 'screen-mapping' refers to the manipulation of computer memory and presentation technology, and is not intended to be confused with cartographic maps *sensu stricto.*

This meant that gradually it became common practice, from the late 1970s onwards, to produce elevation models of mapped areas, which could be derived from existing topographic maps by taking the height data set and establishing it in a computer file or files. Methods of treating data sets for terrain modelling have therefore been discussed quite comprehensively in works such as Petrie and Kennie (1990). For example, by using the **(x,y,z)** Cartesian reference system, where **x** and **y** are the distances north and east respectively from an origin, and **z** is the elevation above the same origin (which can be set at (0,0,0) for the sake of convenience), then a file of elevation datum points can be simply collected and stored. For instance, the height at each grid point intersection could be sampled for a 1:25000 map, and the height estimated by reference to the nearest contours. This method has the advantage that the **x** and **y** positions are inferred from the matrix itself, and they do not have to be coded, providing some information is available to describe or position the origin. This method, of course, saves storage and processing time as the **(x, y)** position is inferred and not stored directly.

Finally, interpolation deserves a mention by itself, as much work has been done in establishing techniques, including (for example) quadratic or cubic splines (2nd or 3rd order polynomial routines), which have been used extensively in the author's research to 'smooth' a surface by increasing the number of points. Kriging is also an important technique and is a term applied to exact interpolation that depends on the probabilistic nature of surface changes with distance (DeMers 2000).

2.3.3 Resolution, Scale and associated problems

The concepts of resolution and its relationship to landform size should be introduced at this point. Resolution is the 'coarseness' or proximity of neighbouring datum points according to the scale being used. The term 'high resolution' refers to data models where gridded or other points are close together and can represent large-scale maps with considerable topographic detail (Kostli and Wild 1984, Makarovic 1975, 1977 and Petrie 1990). For example, gridded points at a regular horizontal distance of 10m would adequately map relatively small landforms - such as drumlins or tors - that could be discerned on a 1:5000 scale map. Lower resolution DEMs would be 'coarser', and perhaps better suited to larger landforms or groups of landforms, such as a drainage system covering many kilometres.

Since resolution is the 'coarseness' or 'fineness' at which map features (and thereby landforms) may be encoded, stored, digitised or treated in any other way by means of computer storage, the relationships and 'trade-offs' between resolution, map scale and landform size are most important here, and this interrelationship has significance for almost every aspect of terrain modelling being used as an 'appropriate and viable technology'.

Map scale may also vary immensely, and where digital maps are concerned may have their attributes determined by 'resolution' - that is - the distance between sampled points in a mathematically represented topography. It is natural that 'large-scale' maps are more detailed and typically cover smaller represented areas, and they are commonly associated (in the UK) with the OS 1:5000 to 1:25000 scales. Small-scale maps are conversely less 'detailed' but represent a larger area. They can range from the OS 1:250,000 maps to Operational Navigational Charts (ONC) for aviation or navigation (note that ONCs are composed of a series of TPCs - Tactical Pilotage Charts - and form part of the same 'set'). These maps are mentioned as they have been used as 'models' or as indirect sources of information in the exercises to synthesise terrain. Indeed, some of the parametric collection methods described in chapter three utilise a range of scales of the same area: 1:500,000 TPCs down to 100,000 and (if available) 1:50,000 scales. The only occasions that large scale maps are used in the research (1:25,000, 1:10,000 or larger) are for the following reasons:

- Checking details obscured or on the edges of smaller scale maps
- Used to gather specialist information (e.g. place names)
- Used to model fine detail, such as tors and boulder fields, although this was seldom done: micro-terrain is treated only in chapter six.

The relationship between scale, resolution and volume becomes self-evident: high-resolution of detail tends towards large-scale maps with landforms measured in tens, hundreds or thousands of metres. Smaller scale maps could use coarser resolution data sets to represent larger landform structures, such as drainage systems, measuring from thousands of square metres to many square kilometres. Some of the volume considerations are outlined below in the appendices on Information Technology.

Another stumbling block is the use of the word 'scale'. Some geomorphologists refer to 'small-scale' features when they mean 'physically small' landforms (Dahl 1965), yet they would access them using 'large-scale' maps. Griffin (1977) referred to very small features - measuring metres across - as 'micro-morphology'. This usage is quite proper, if unfortunate, as many laymen have small-scale and large scale maps confused.

Therefore, for clarity in this thesis, the terms 'small-scale' and 'large-scale' are avoided unless strictly necessary, and the 'resolution' of maps will be dealt with directly by reference to the actual scale (e.g. 1:50,000) or to the distance between gridded, interpolated or non-gridded datum points.

2.3.4 Photogrammetry and real data collection

This thesis is concerned with synthesised terrain data in various forms, representing both real-world physical regions and 'typical' or textbook assemblages of landforms, or a composite of the two. It is necessary, however, briefly to consider how real data would be collected in order to stress the contrast between synthesis and 'reality'. Data acquisition is vital for collecting accurate three-dimensional digital models of terrain (Kennie 1990), whether the application is mapping and surveying, mining, civil engineering or any other reason. Data collection may be done by laborious and often expensive methods, including field data collection (Kennie 1990, Gorham 1988 and Grant 1981), photogrammetry - which involves the processing of aerial photographs (Petrie 1981, 1990, Webb 1990) and specialist methods such as the MOSS survey system (Craine 1990).

Whatever the method, there are always common denominators for collecting accurate and high resolution data, namely:

- The need for accurate and time-consuming field data collection or aerial photography/remote sensing

- The need for accurate, careful processing of the results, often using expensive equipment
- The need for some manual input, as no system is fully automatic.

These are not criticisms but comments on the techniques. Field data collection must take place if science and technology, not to mention the general public, are to have access to detailed topographic maps and (via GIS tools) terrain models and exploitation of spatial data. Indeed, many applications will produce special purpose models (such as remote sensing Infra Red - (IR) - technologies - mapping for land use etc.). However, whatever the application, it is expensive and time consuming to collect data for a DTM covering even a small area. This, and the fact that commercially-available DTMs are either state-controlled or prohibitively expensive (or both), makes the notion of creating synthesised terrain models more attractive in certain circumstances. It should be noted, however, that new technologies and systems are improving the general techniques for remote sensing and data collection (for example the Lidar system). Naturally, where a real world, accurate DEM or DTM is required, there is no substitute for photogrammetry or 'real-world' data collection, and synthesised terrain is not required - the point is that synthesised terrain models and real DTMs both have a part to play until DTMs at every scale and of every area are cheaply or freely available, and even then there could be uses for the genre.

Alternative methods of collecting and storing DEMs depend on whether maps exist or not. Clearly a DEM can be created easily, and the 'raw' data can even be collected manually (Griffin and Gilmour 1981) when existing map data is available, but the problem is significantly increased if there are only small-scale maps of the area concerned (indeed, this is also a reason for wishing to 'synthesise terrain'). In this case, data sets have to be collected by manual or automated surveying methods, aerial photography or satellite imaging, thereby underlining the importance of these techniques.

A final point is the increasing use of the Lidar technology (Light Detection and Ranging). This technology requires an aircraft or remote sensing platform, but early predictions suggest that the cost of photogrammetry (and therefore of producing DTMs and DEMs) may be significantly reduced. Lidar is examined in more detail later in this chapter and in the appendices.

2.3.5 The role of the earth sciences in synthesised terrain

(a) Geomorphology

Geomorphology plays a vital part in synthesised terrain, as it is only possible to produce 'high-fidelity' landscapes - i.e. where the synthesised terrain is 'realistic' or 'geomorphologically-viable' - if an intimate knowledge of the various types of *possible* landscape is acquired. Geomorphology is considered by far the most important of all the overlapping disciplines and technologies that contribute towards synthetic terrain for obvious reasons - geomorphology is the study of the earth's surface and forms a crucial background to the work described in this thesis.

It is one of the main themes of this thesis that the application (and appreciation) of geomorphology is one of the most important areas associated with synthesised terrain, and an understanding of geomorphology allows maps of high fidelity to be achieved. Therefore, geomorphology is felt to be important for several reasons:

- Geomorphology has had decades of research and comprises a massive area of study in many languages. It is therefore the only branch of science that can be used to measure, calibrate or assess the veracity of attempts at producing synthesised terrain.

- There is a wealth of literature concerned with geomorphological research, and of great importance, many works have been completed by 'computer-literate' geomorphologists.

- Geomorphology - although perhaps not an 'exact science' - is characterised by statistical analyses and a tendency toward using numerical approaches to solve problems, in combination with theory and practice (e.g. fieldwork). This abundance of statistical work is also available to help measure and make critical assessments of the characteristics of synthetic terrain.

- Geomorphology can be linked to other areas of science which are also of use to this thesis. This is what is meant by the 'overlapping disciplines and technologies' mentioned above. These include geology, hydrology, glaciology, geophysics and other earth sciences, as well as statistics, computer sciences, satellite technology, some representatives of the life sciences (such as spatial vegetation patterns) etc.

Indeed, geomorphology is considered so important that IT and computers are merely a 'means to an end' - they are tools - whereas geomorphology is the 'touchstone' that helps create synthetic DTMs and DEMs of sufficient quality and realism that they can be used in real-world situations, for training, simulation and general display purposes.

Clearly, in the real world, landscapes (and the landforms of which they are composed), will change with latitude, climate, geology, changes in environment, the effects of man and vegetation, the importance of land use, and many other factors. This means that the worker attempting to reproduce or synthesise terrain must draw on basic geomorphological concepts in order to be able to associate these with the model, if desired. This is a two-edged situation, as the great wealth of literature and research done in the field of geomorphology means that there is an enormous amount of information that can be accessed. Some of this information, will, of course, comprise contradictory theory, thereby adding to the problem of sorting through the *genre*.

Moreover, there is a profound if oft-quoted saying - fondly used by those in a position to set undergraduate examination questions - that:

'truth in geomorphology is little more than increasing probability'

Discussions with geomorphologists tend to place geomorphology as an 'inexact' science, since so much speculation and guesswork must accompany even the most rigorous analyses. To offset this, geomorphology is a well-documented science, since so much of the subject is rooted in time spans and chronologies - landform developments must often outlast the life span of the worker studying them by many orders of magnitude. Looking on the positive side, geomorphology has a lot to offer the worker who wishes to synthesise terrain; indeed an understanding of geomorphology is the only real way in which validation and fidelity can be recognised and applied. Similarly, the worker can also apply geomorphological concepts to aid in the creation, update and validation of the synthesised terrain, as well as the 'editing' of already synthesised terrain (so that the fidelity is kept to within certain bounds of 'realism') and even the so-called 'augmentation' of real terrain (see chapter nine).

Geomorphology, as stressed above, has its special place in the field of synthesised terrain, and therefore is a theme that is examined (with references where necessary) throughout this thesis, depending on the application. Other fields in the earth sciences contribute to the development and exercise of terrain synthesis applications, and these will be examined below.

(b) Hydrology - general relevance

Hydrological applications for real and synthesised terrain have produced some interesting works, notably those concerned with 'automated landscape parameterization'. Such works (e.g. Garbrecht and Martz 1996) have examined the treatment of depressions and flat surfaces in the DEM, as well as the indexing of channel links in raster generated networks. Garbrecht and Martz (1996) pointed out that automated drainage identification, watershed segmentation and catchment parameterization from raster DEMs has been emerging as an *'attractive source of topographically derived data . . . for hydrological modelling'*. They mention simple extraction procedures that can lead to inaccuracies (Quinn *et al* 1991, Tribe 1992, Martz and Garbrecht 1995), and identify the D-8 method of downslope flow routing (Fairchild and Leymarie 1991). Although the models can produce 'synthetic' terrain the purpose appears to be related to GIS and hydrological techniques rather than attempting to create geomorphologically-sensible DEMs. Moreover, some real world catchment areas are used as references or sources for DEMs, so the synthesised terrain element is inferred rather than a main topic. Subcatchments are also considered as important elements in the parameterization process, and work done by Wooding as long ago as 1965 is used in this context (Wooding 1965).

Wiche and Jenson *et al* (1992) attempted to model hydrological areas in the United States, using DEMs and attempting to assign costs to synthesised terrain. Interestingly, they used the concept of 'contributory' and 'non-contributory' surface areas, which they described as 'hydrologic characteristics'. Contributory areas were defined as those actually putting water into a drainage basin, and by this method they hoped to estimate flooding.

Hydrology was also examined in a work edited by Beven and Moore *et al* (1992). Here, digital elevation data is used to examine hydrological, geomorphological and biological applications. (Moore *et al* 1992) concluded that the topography of a catchment area has a major impact on the various processes (hydrological, geomorphological and biological) active in the landscape. They also opined that the spatial attributes exhibited indirect relationships. In the same source work Quinn *et al* (1992) looked at the prediction of hillslope flow paths for distributed hydrological modelling using DTMs. Again, a real-world area is examined, this time using a collection of software models called TOPMODEL.

(c) Taxonomies

At this stage mention should probably be made of taxonomies of landforms and landscape units, since many attempts at breaking down areas in the real-world depend on such classifications. The paragraphs above deal with landscape units and scale (see Table 2.1) and we have already seen how the terms 'basin and sub-basin' have been used by Wiche and Jenson (1989). Again, there are many workers who have attempted to put forward taxonomies, and only a few can be listed here. Penck (1874), W.M. Davis (1896), Savigear (1965), Bausch (1969), Kugler (1974) and Speight (1973, 1974) together form just a sample of some 'classic' early workers. Speight discussed descriptors for classifying objects (e.g. form facets and form objects), whereas Ahnert (1996) gave a useful indication and guide to scale versus duration (Fig. 2.4).

(d) Slopes, surfaces and interpolation

C.M. Gold (1992) examined surface interpolation - this is a topic that has already been mentioned as being crucial to terrain modelling and terrain synthesis. Gold looked at triangular plates and interpolation as a means of smoothing landscape surfaces. There are many different

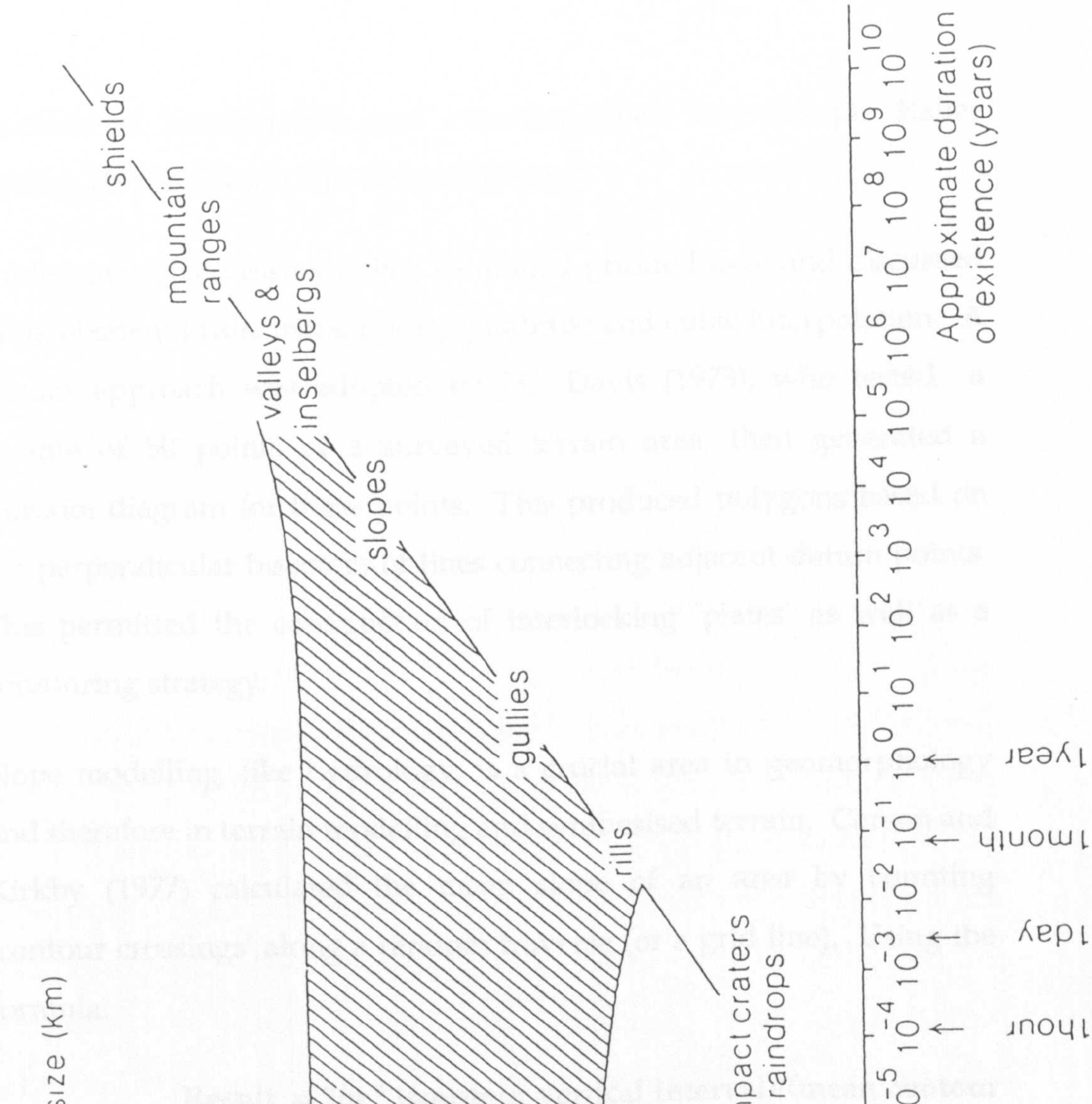


Figure 2.4 The relationship between size types and duration of geomorphological objects (After Ahnert and others)

methods of interpolation and smoothing (see for example Raper (1989a), (1989b), Petrie and Kennie (1990)).

Andersen and Woessner (1992) examined gridded data and discussed finite element grids, using linear, quadratic and cubic interpolation. A similar approach was adopted by J.C. Davis (1973), who tested a sample of 50 points of a surveyed terrain area, then generated a Voronoi diagram for these points. This produced polygons based on the perpendicular bisectors of lines connecting adjacent datum points. This permitted the construction of interlocking 'plates' as well as a contouring strategy.

Slope modelling, like hydrology, is a crucial area in geomorphology and therefore in terrain modelling and synthesised terrain. Carson and Kirkby (1977) calculated the mean slope of an area by counting 'contour crossings' along a random traverse (or a grid line). Using the formula:

Result = 2/π * ((contour vertical interval)/(mean contour separation along traverse))

they were able to construct various slope profiles in known drainage basins. The concept of a 'contributing area' was discussed; a subject also examined by Betson (1964) as the peak stream runoff divided by the peak rainfall intensity. Betson argued that a result <10% would typify an area with 'good soil and vegetation cover'.

It should be recalled that although process and process-response models are used in this research study, it is the portrayal of the form rather than the process that most interests the 'end-product' synthesised terrain. For this reason a considerable number of papers and works on slope process have been examined briefly, but have not been included in this work, as it is the morphology that is of most interest. Separating 'form' from 'process' can be controversial in geomorphological research, but the 'terms of reference' of the work were directed at simulation end-products, and geomorphological 'validation' was sometimes only a 'luxury' in the eyes of the sponsors.

Slopes are typically portrayed on morphological maps in terms of direction of slope, convex and concave elements, free faces, breaks of slope and other features (see Young (1975, 1976), Clowes and Comfort (1998), page 49). Finlayson and Statham (1980) also gave a simplified discourse on convex and concave slopes, and they discussed slope recession processes such as weathering and landslides. They also framed a well-known expression in geomorphology that *'form tends towards an equilibrium during the prolonged operation of a process'*. Indeed, one can also invoke, as far as process modelling is concerned, the well-known concepts of 'gradual' and 'catastrophic' slope recession, where gradual processes like weathering (which is the gradual destruction of rock fabric and other surfaces over decades and centuries) can be contrasted yet linked to catastrophic processes (such as landslides achieving many metres of erosion over a few short hours). The concept of catastrophism is important and was examined carefully as a possible modelling technique referring to (among others) works such as Hutton (1785, Holmes 1972, 1978, Renton 1994). Naturally such models, and the concepts behind them (many of which are derived through the years from the 'classic works' of such authorities as C.A.M. King. D.L. Linton, R.J. Chorley and many others), are of intense interest to terrain synthesis workers attempting to put such derivations 'into reverse', as it were, and construct terrain from 'first principles'.

2.3.6 Terrain Synthesis

The field of 'pure' terrain synthesis; that is, creating terrain for its own sake, is relatively new, and few references exist. This is not surprising, as almost all users of DTMs and DEMs derive their data from real parts of the world, and there has been little need to create artificial landscapes, except for special effects, or for particular applications (where the cost and availability of real data sets became a limiting factor).

Some of the early work involved in trying to synthesise 'geomorphologically-viable' terrain was, in some ways, a reaction to the perceived unsatisfactory and simplistic explanations offered by those non-geomorphologists who were using fractals and self-similarity to simulate objects and landforms in a general sense (Mandelbrot 1982). Private correspondence by the author with some UK geomorphologists in the late 1980s revealed a general reaction against the use of fractals alone in explaining coastlines and mountains (apparently sparked off by Benoit Mandelbrot's milestone works of 1977 and 1982), as this appeared at the time - perhaps unfairly - to ignore or reject a century of careful geomorphological research.

This response was hardly surprising; exponents of fractals had come from the mathematical disciplines, they were not particularly sensitive to geomorphological research and they were initially perhaps rather too enthusiastic in their claims regarding the description of complex terrain by mathematical techniques and 'self-similarity' alone. In short, Mandelbrot and others have not been recognised as authorities in the earth sciences, no matter how brilliant their mathematical achievements may have been. For example, Andrle (1996) - to take one example - has been less than convinced that fractals are of use for certain areas of geomorphology.

However, now the record appears to have been set straight, as fractals are acknowledged as being important components of landscape synthesis as far as mathematical methods and stochastic processes are concerned, and a balance (if not a complete acceptance) has been achieved. Although the work appeared late in the PhD research to be included in the algorithms, Rodriguez-Iturbe and Rinaldo (1997) produced some useful fractal-based observations, and effectively linked geomorphology, hydrology and mathematics. These authors considered river basins and drainage networks in the light of their scaling and multi-scaling properties, and the dynamics responsible for their development. Their work on the hydrology and prediction qualities of river basins demanded a knowledge of fractals in terms of a range of temporal and spatial scales, including the search for the 'hidden order' of these temporal and spatial variables in river basins, despite variations in climate, scale and geology. Other examples of workers using fractals include Snow (1989) and Nikora (1991), who regarded meander traces as fractal structures, but only within the context of carefully controlled models where there is input from trained Earth Scientists and/or cartographers. Polidori (1995) used fractals to evaluate relief mapping techniques and textbooks have appeared about the use of fractals in the geosciences (for example see Wilkinson *et al* 1995).

Since almost all geomorphological models are based on research into actual areas, it may come as something of a shock to some geomorphologists to confront the reasons why one would wish to create artificial terrain at all.

2.3.7 Terrain Modelling: Real Terrain

Terrain Modelling of real-world data sets needs to be examined in outline for two reasons; first in order to understand why synthesised terrain is important, and second, because the set of techniques and terminology is virtually identical to both synthesised terrain and 'normal' digital terrain. This helps address the question *'why use synthesised terrain data instead of real DTMs?'*. Moreover, there is no reason why synthesised terrain models should be treated any differently from real world DTMs in terms of storage, manipulation, presentation and other features. However, this is a vast subject, and it is additionally relevant in the sense that techniques and concepts can be borrowed or reused to 'make' synthesised terrain.

As Ahnert (1996) has said, the use of models is almost as old as geomorphology, and one only has to call to mind some early workers including Gilbert (1977), Davis (1899), Penck (1924), Baulig (1940), King (1957), Wooldridge and Linton (1957) and Budel (1963) among many others to envisage the range of important, pre-computer age or 'early' attempts to model and understand the landscapes in which we all live.

'Real World' terrain modelling at a detailed level; that is the computer modelling of actual physical areas as opposed to synthesising them, with the many techniques involved, is an important and interesting area. This was developed over the last few decades, as IT resources presented academics, scientists and technologists with the means and opportunities to construct fast, effective and useful software to manipulate what have become known as DTMs and DEMs. The creation, management and visualisation of such models has always been important, and a considerable amount of literature exists on the subject.

Not surprisingly, since computing 'power' was not originally in the hands of the early geomorphological workers - much of this work was originally derived from 'pure' computer graphics (Appel 1968, Newman and Sproull 1979, and many others) and then became applied to the earth sciences in one form or another (Tindall *et al* 1986, Schachter 1980, McCullagh 1988). However, geomorphologists were, of course, perfectly capable of drawing their own conclusions about the capacity for IT to support DTMs and DEMs, and a wealth of literature exists on techniques, applications and models. This period (the 1960s through to the 1980s) appears to have coincided - in the author's view - with the period when geomorphologists and other Earth Scientists became 'computer literate' and had more direct access to IT resources.

Most of this work is targeted at real-world areas, since there is no reason not to, and the real world has the obvious advantage in that theories can be tested against observations, or *vice versa*. A standard work referred to in this chapter is 'Terrain Modelling in Engineering and Surveying' (edited by Petrie and Kennie 1990), which usefully identifies and outlines the techniques from real data collection (photogrammetry and survey) through to some of the more abstract applications - including synthesised terrain.

2.3.8 General Modelling

Modelling in the earth sciences - particularly in geomorphology - is, of course, a well-known and long established general technique. Models to help explain the form, process and timescales involved in creating landforms and landscapes. Models range from theoretical types, to highly detailed mathematical models involving detailed (large-scale) maps.

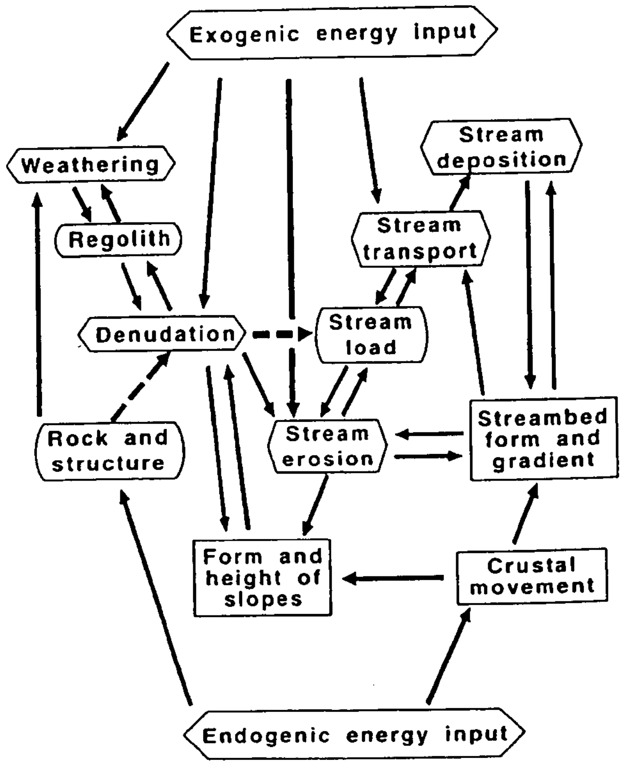
The type of geomorphological modelling that concerns this work is that which deals with landscape and landform creation, such it is the morphology (the 'form') rather than the process that is desired in most of the projects that make up the author's composite research. This does not preclude process and process-response models, as these are one way of attaining realism. Some of the more detailed models (e.g. rate of growth of metre-size glacial bedrock features by workers such as Dahl (1965) and Gjessing (1967)); the chapter in Embleton and King (1971) on small scale features of glacial and fluvioglacial erosion, as well as very detailed, recent measurement-based work on rivers (see Knighton (1998) for a comprehensive list) may have relevance for as specific area or map scale, but in general it is the medium to macro-level or scale that is of most significance. In other words, scales of 1:50,000 are about as detailed as the landforms need to be, although some larger scale maps are used in this thesis (notably in the attempts to simulate tors in chapter six).

Recently Ahnert (1986, 1987), who has been responsible for a considerable amount of research in geomorphological modelling, producing a work entitled 'The point of modelling geomorphological systems' (Ahnert 1996, in McCann and Ford 1996). He reviewed various types of modelling, including *static modelling* (where components and functions are used), to *process modelling*, to *process-response modelling*, which combines the first two categories and may be characterised by feedback (see Figure 2.5). Ahnert therefore postulated three types of model:

- Static models - the fundamental relationships between components
- Process models - concerned with rates and processes
- Process response models - feedback is taken into account

It is proposed to adopt these terms - such as 'process-response' - as they admirably suit some of the algorithms in the terrain synthesis software described in this thesis. Ahnert (1987) also used a program called SLOP3D to model some of his theories, which parallels some of the author's own researches into creating slopes from planar surfaces, but through quite different methods and for different reasons (Figure 2.6).

It should be mentioned that some geomorphological models have been created in attempts to create 'ideal' or 'stylised' landforms in order to study form or process, among them Chorley's (1959) 'streamlined' drumlins - where drumlins are compared with aeroplane wings and snow drifts (Embleton and King 1971) , and Reed *et al* (1962), who attempted to model drumlins by approximating an ellipsoid of the derivation:



Components and interactions of the fluvial landform system (schematic)

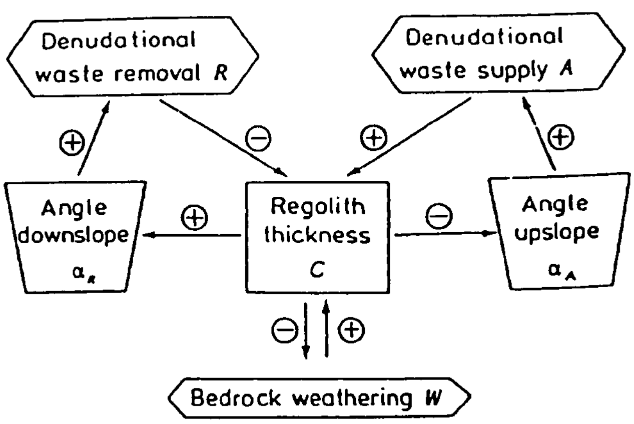


Figure 2.5 Feedback and System Models - after Anhert (1987).

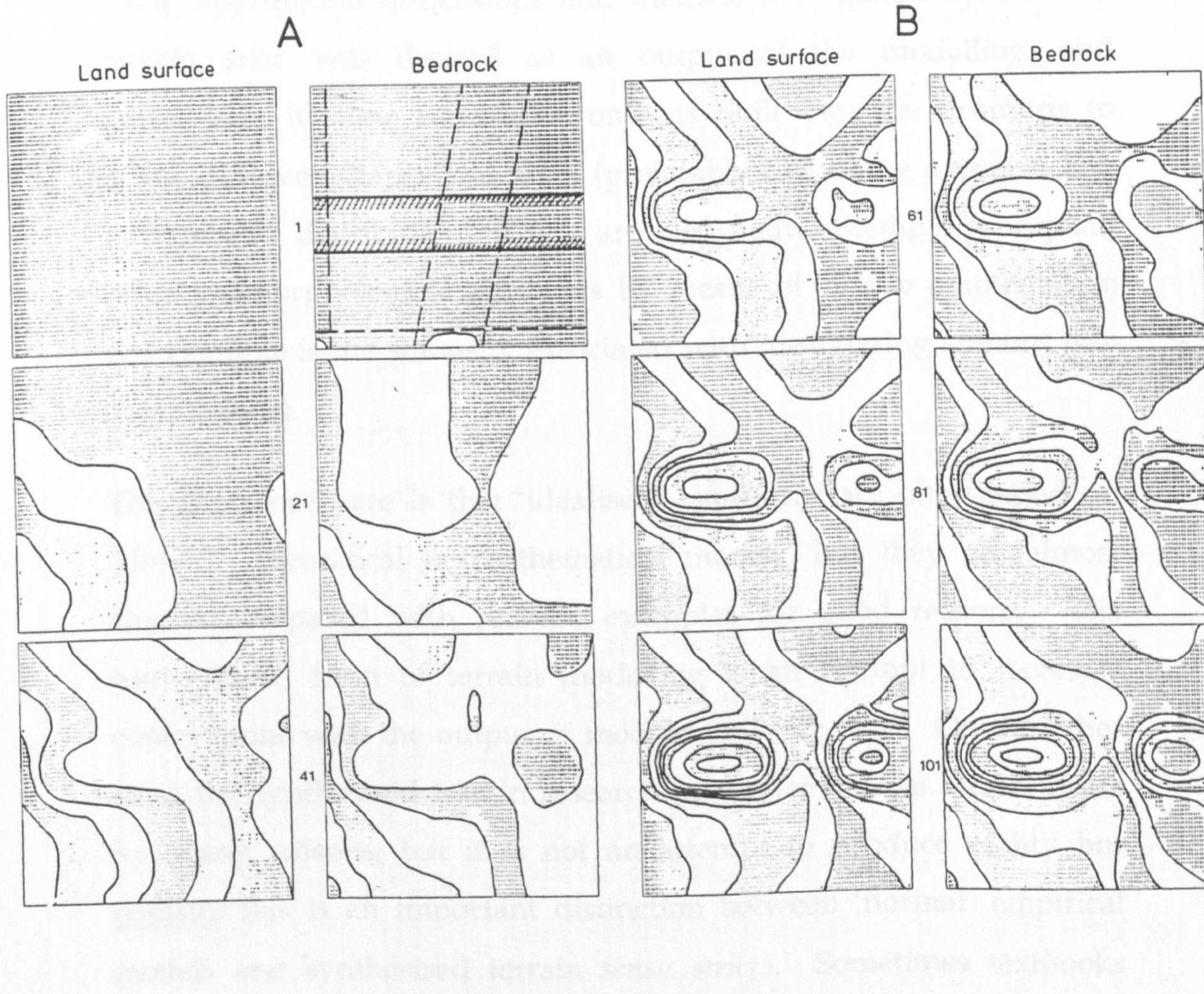


Figure 2.6 SLOPD3 model of shield inselberg development through downcutting and denudation over simulated elapsed time units (numbered) - After Anhert (1987).

$$X^2/a^2 + y^2/b^2 + z^2/c^2 = 1$$

Where *a, b* and *c* are the long, intermediate and short axes respectively, and *x,y* and *z* are Cartesian co-ordinates. Field observations by the author in Yorkshire showed (unpublished work) - not surprisingly - that drumlins only approximate this form, they do not adhere exactly to it, as Chorley himself possibly would have been the first to admit. However this formula could be used to create 'fields' of drumlins, using appropriate dimensions and metrics, if a 'glacial synthesised terrain area' was desired as an output of the modelling, and particularly if some randomisation was built into the drumlins to create different shapes and sizes (preferably describing a statistically recognisable distribution). There are also many attempts to explain other geomorphological attributes by means of simple mathematics; one example is the sinuosity associated with meandering streams (see chapter four).

The difference here is that 'idealised' landforms are often based on 'close-fit' theoretical or mathematical models, but they are almost always compared with real-life examples for good reasons. The conventional form of terrain modelling is an attempt to reconcile observations with the output of models, and *vice versa*. On the other hand the synthesised terrain research may refer to 'real world' areas for many reasons, but it is not an attempt to produce reality but realism: this is an important distinction between 'normal' empirical models and synthesised terrain *sensu stricto*. Sometimes textbooks simply draw on 'artistic impressions' or diagrams of what they regard as 'realistic' 3D terrain in order to illustrate some point. No attempt is made to produce realistic or geomorphological sensible terrain, as far as is ascertained, yet a convincing 3D landscape is still produced all the same. A good example is to be found in Aschehoug (1979) which explains the relative disposition of sea and land with regard to sailing techniques and wind effects, where a beautifully detailed 'artists impression' of a land surface is reproduced in 3D. It could pass for a 'real' surface - but it is apparently entirely imaginative and is used only for illustrative purposes.

2.3.9 Use of IT: General (The development of computer techniques for terrain modelling and mapping)

As the previous paragraphs have shown, the reasons or even the concept of modelling terrain would have been pointless without the advent of the digital computer; indeed the terms 'DEM' and 'DTM' are products or 'by-products' of the 'great IT revolution'. This is not to say that terrain was not modelled before the advent of widespread computing facilities - indeed many mathematical models of existing features were attempted in order to find general derivations or principles that might describe them (Chorley's 1959 drumlin model is a good if rather detailed example of a idealised three-dimensional landform). Also, hardware models of terrain were prepared for a variety of reasons, including display, education and artistic reasons.

However, the advent of IT, first with mainframes - large expensive batch-mode computers - in the late 1960s, the 1970s and then with the so-called minicomputers and microcomputers of the 1980s, changed the face of the whole genre. The recent innovations to provide almost all technologists and scientists with powerful computing, network bandwidth and electronic communication facilities (that would have been thought absurdly extravagant in the 1970s) is a process now well underway.

The following paragraphs outline some of the improvements and innovations relating IT to DTMs, the earth sciences and cartography over the last twenty years or so. This is relevant; and it should be pointed out that, as far as 'real-world' terrain modelling is concerned, generally the main techniques are equally appropriate to synthesised terrain modelling. Several key methods are adopted, and indeed some were altered by the author or derived from other workers in the chapter on methods (chapter three) in this thesis.

2.3.10 Overview of IT development: general

An example of early DEM derivations were the UK Ordnance Survey (OS) digital data sets available from the 1980s up to the present day (ref. *Ordnance Survey Digital Products Catalogue 1994*), where the data sets were exclusively vector-based, as the whole point was to reproduce facsimiles of the lines of a large-scale map by means of a plotting device, such as a flatbed plotter. To do this, the OS initially provided a FORTRAN IV computer language program to interpret the data files and to facilitate the plotting. The digital data sets, at that time, had only a limited coverage of the UK, and were, of course, based on real areas. The advantages of plotting one's own maps at various scales is acknowledged, but no manipulation of the data sets was possible and the package was considerably expensive.

After the mid 1980s, the technology of computing processors and display devices became almost unrecognisably improved. New UNIX machines, and the powerful PCs (Personal Computers) that complemented them, were at the forefront of the GIS 'revolution', allowing maps to be displayed rapidly and accurately. It was possible, for example, to scan a digital image of a normal cartographic map (such as a 1:100,000) to produce a raster-based digital map. This could then be displayed, with zoom and other features - such as height information from an affiliated DEM source - on the screen.

There has been a dramatic increase in power, performance and general resources in all areas of computing hardware over this time. But at least the era of 3GL (Third-Generation Language), while it did not have

GIS systems or powerful computers as everyday tools, meant that the availability of a good structured language (such as Ada or FORTRAN V) could be used for some of the complex algorithms - by means of writing one's own software modules. A 3GL and a 4GL (Fourth Generation Language) are defined in Appendix B.

The investment work undertaken by the government and private industry in by the 1980s and early 1990s producing 3D viewing routines and contour plotting programs. These in turn yielded dividends in helping the author understand the genre (although these too were to become semi-redundant as more GIS products reached the market). CPUs became almost unrecognisably fast, and just as significant are volume comparisons; these are the amount of hard disk and on-board 'volatile' memory available per monetary unit over time. The standard resident memory in today's PCs, whereas larger machines will have on-board volatile memory volumes of several GigaBytes (see HP or Sun UNIX machine specifications as examples).

Similarly, disk space has changed from a typical 2 MegaBytes in the mid 1980s to a typical 10 GigaBytes today (an astonishing five thousand times increase). Indeed, even in the mid 1990s the term *VLDB* (Very Large Data Base) was used in the Relational Database industry (Oracle 1991), and conferences were held to help users cope with the performance degradation of such unthinkable volumes. Yet at this time only 10 GigaBytes qualified as a VLDB; now the term has fallen into disuse as TeraBytes databases are quite common (1 TeraBytes = approx. 1000 GigaBytes). The author can think of no comparative area of science or technology where the increase has been so dramatic - even the increase in the speed of aircraft (120 kph in 1914 to 4000 kph in 1960 - Gunston 1976) does not compare with these figures.

To take an example of a 'normal' Personal Computer (PC) system: a personal computer with >5 GigaBytes of disk storage (or 5000 Megabytes), >256 Megabytes of on-board memory and processors with a rated speed of more than 500 MHz are considered the norm per person at the time of writing, although already there are signs that higher speeds, even more bandwidth and yet more storage is required. No doubt these figures will increase - perhaps double over the next years unless different technologies are used. Indeed - at the time of writing - a 1 GHz Xeon chip has been announced (*Computing* 31 August 2000) - and PCs with CPUs of >1 GHz are already available as this thesis 'goes to press'. As far as disk storage (known as 'volumes') are concerned, some Oracle databases now deal with PicaByte size storage capabilities, which are units of thousands of TeraBytes (this is about one million Megabytes). Although at first glance this is large (and typically are used for RDBMS census or financial systems), such volumes might also be necessary for the vast data files that can be needed for raster maps and DEMs. For example, consider a DEM file of 10km X 10km (100 km^2), with a resolution (the horizontal distance between points) of 100m. Allowing a byte (8 bits) for storage of the height (where the **x** and **y** positions are inferred from the file column/row position), and two bytes for terrain attributes, this would yield 101 X 101 points (10201 points) times 3 bytes to give a file size of about 30.5 Kbytes. However, increasing the resolution to 10m would push this up to over 3 Megabytes; clearly the square rule is at work here.

This individual set-up is often complemented, at the University or 'business departmental' level, by connectivity with a centralised server, often a multi-processor NT or UNIX-based machine of considerable power and storage capability. The connections are enabled by networks of sufficient bandwidth, either as Local Area Networks (LANs) or through routers and hubs to Wide Area Networks (WANs), facilitating communication via electronic mail or other media to virtually the whole of the electronic community of users. The Internet - the connection of global WANs and LANs that comprises the World-Wide Web (WWW) has grown exponentially, from 213 hosts in August 1981 to almost 20 million hosts in late 1997 and an estimated 70 million hosts in late 2000 (Wherrett 1999, Comer 2000).

These are the tools (together with scanners, digital cameras and high resolution colour printers) that permit users to manipulate and view landscapes, and the pace of technological change has allowed progressively more ambitious projects to be realised. In such a world, minor areas of previously only academic interest (such as fractals) have become world-wide tools of an ever expanding and 'concept-hungry' web-based technological society.

2.3.11 Use of IT in the earth sciences - relevant examples

IT has provided a host of workers the facilities to manipulate and experiment with DEMs and DTMs. Most universities have IT facilities, and even during the four-year duration of this thesis compilation, the author has noticed the 386 (60 MHz) processors at the University of Nottingham become replaced by considerably more powerful personal workstations of 400 MHz up to 700 MHz or more, with perhaps ten times as much memory and disk storage space. This has also coincided with the expansion of the internet and the many sites catering for every scientific (and non-scientific) subject. Some URLs (Universal Relative Locators) for selected terrain modelling web sites are given at the end of this chapter.

It is worth commenting that computer programs may appear conceptually-difficult or abstract to some people, yet by definition, they must be ultimately and unequivocally presented to the central processing unit (the CPU) as machine code in binary form (i.e. the bits set to 0 or 1 that every digital computer eventually must access), having been compiled or interpreted via some convenient high-level language such as C, C++ or FORTRAN.

The spatial importance of IT has, of course, been apparent to physical geographers and geologists for many years. Students in UK undergraduate courses in the early 1970s - the author among them - were allowed to present Hollerith card FORTRAN programs to the ICL mainframe (at the University of London). However, there were no interactive graphics or what we would today call 'GUIs'. Early exponents of 'geoscientific data graphics' about this time were Sprunt (1970, 1975) and Davies and McCullagh (1975). Later, authors such as Raper (1989a, 1989b), examined the three-dimensional applications of geographical information systems. McClaren and Kennie (1989), and Kennie (personal correspondence, 1989), produced a critical review of the samples of real terrain (expressed as DTMs), and discussed the visualisation of digital data.

This is an important area of work, in the sense that authors such as Petrie and Kennie rightly join together and cross-reference the existing and emerging works that link the power of IT to geomorphology (see for example Ahnert (1987), Armstrong (1976, 1982, and 1987), Craig (1980) and others), together with IT applications, synthetic terrain (Griffin 1987) and the important area of stochastic modelling using fractals and Brownian motion (Mandelbrot 1982 and Van Ness 1985). The impact of a good graphical user interface (GUI) is also examined by Raper, and indeed this is perhaps one of the first of the emerging books and papers in the earth sciences to mention visualisation using texture and surface features (Raper 1989). Previously, few authors had used IT to visualise or analyse landforms (Davies and McCullagh 1975) and early examples of computer 3D views before GIS systems were commonly available (or even ever known as 'GIS') are represented by Sprunt (1970, 1975) and Griffin and Gilmour (1981).

Again in work edited by Taylor and Francis (1989), Dikau (1989) used a digital relief model to aid landform analysis in geomorphology. Dikau explored modelling terrain into 'relief units', but again real terrain was used as the focus for the modelling. The end of the 1980s was thus an important time for terrain modelling and geomorphologists who wished to use DTMs and DEMs - many reasons may be given for this, but one obvious point is simply because the massive leap in computer and 'workstation' power meant that such compute-intensive areas of research could at last be available to almost anyone.

2.3.12 Cartographic and GIS influences

In the 1970s and early 1980s, some workers simply did not have access to IT. Those that did had storage tube displays and pen plotter devices available to them, but these could only realistically handle vector data - they could not be expected to plot raster data, which was best left to the emergence of powerful raster display devices and inkjet printers in the mid 1980s. Users were forced to create their own DEM management and visualisation software (Griffin and Gilmour 1981) in the absence of the rich selection of GIS packages available today (DeMers 2000). Rhind (1981), for example, complained of the lack of commercially available tools for handling spatially-distributed or 'geographical' data. Indeed, the software for interpolation routines, Kriging, DEM management software and 2D (contouring and relief shadowing etc.) and 3D (depth-factoring perspective or true perspective views) - in fact all the features that are taken for granted in today's GIS technology - were probably written at several places around the world simultaneously. For example, the author wrote several software packages in the 1970s that are still in use at MOD sites to this day (Gilmour and Griffin 1979, 1980(a), 1980(b)). Linear, quadratic and cubic interpolation techniques were also frequently used (Petrie and Kennie 1990).

Naturally a DEM data set still had to be collected and synchronised with the position and screen co-ordinates of the raster background map. This allowed 'windows' to be created that would display the height at any point on the screen/map (usually driven by a pointing device such as a mouse/cursor), often with intervisibility plots and other refinements (including mean height of displayed area, mean slope, Lat./Long. etc.) that could be overlaid as vector plots on the screen. Intervisibility is the property of two or more points being visible to each other - usually in the context of a topographic surface (DeMers 2000) and the applications and usefulness of intervisibility is discussed in more detail in the next chapter. Such a system, based on ONC 1:500,000 maps of North Europe, was built and supplied by the author (while working in industry) to *HMS Dryad* (Royal Navy) in 1989, predicated on Sun Microsystems UNIX workstations using OSF/Motif and the now-defunct relational database known as Ingres. In effect, this was an early GIS, with the added benefit of an RDBMS (Relational DataBase Management System) query facility.

During the 'pre-GIS' period automated mapping or geographical data management systems had to be customised and the software written 'from scratch'. For example, in the 1960s work was done in Canada (Tomlinson 1984) to assist with forestry and rural development which was such a galling task that, effectively, a 'GIS for Canada' was required (DeMers 2000) even though it would be years before the tools were available. However, the situation has changed dramatically in the decades leading to the 1990s, as computer vendors and software houses began to create the circumstances whereby the acronym 'GIS' would be a familiar part of IT terminology (Maguire *et al* 1991, Rhind

1992, DeMers 2000). A GIS can be considered as a computer system that can acquire, store, modify, process and display spatially-referenced geographical data. Nowadays there are many 'off-the-shelf' packages for GIS systems, most of which run on PCs, UNIX systems or 'Apple Mac' machines. Examples are Arc-Info (ESRI - Environmental Systems Research Institute), Intergraph and Formida, to take examples at random. Some GIS products can be linked, for additional functionality and power, to relational database management systems (RDBMS) such as Oracle, for example (see the next section).

Many more digital maps, DTMs and DEMs of all types exist these days, and digital mapping coverage of the UK and other countries has expanded considerably. Mapping and general cartographic uses have been described by several authors, and recently specialist periodicals and learned journals have come into being to support this growing branch of the geosciences. As far as terrain models are concerned, Burroughs (1991), Bernhardsen (1992) and Heywood *et al* (1998) form a good series of references, although there is considerable choice.

As far as synthesised terrain is concerned, references are scarce. Petrie and Kennie (1988) probably produced one of the earliest rigorous papers on the topic, as they reviewed the use of fractals in terrain synthesis and examined the elements that make up 'realism'. Li Fang (1994) described an automated generalisation system for large-scale topographic maps, using a computer system called ASTRA at Hanover University (for a general description of ASTRA see Leberl 1986). The ASTRA system was also used by Leberl *et al* (1985), while Opheim (1982) discussed rapid methods of data reduction in a digitised curve. Li Fang also argued, agreeing with Brassel and Weibel (1988) that since maps are simplifications or generalisations of reality, then all maps are simplified abstractions of reality. Li Fang used various methods to change scale (e.g. from 1:1250 to 1:10,000) and assessed the changes that occurred (e.g. loss of accuracy), and although this is not the same as synthesised terrain cartography, there are clearly overlapping concepts.

Automated maps, as tools for geomorphologists, have been more useful in the last 10 - 15 years because of the increase in IT applications. Brassel and Weibel (1988) reviewed conceptual frameworks of automated map generalisation, and interestingly saw map 'generalisation' as a 'bottleneck' in GIS processing, while Lichtner (1979) examined computer-assisted processes of cartographic generalisation in topographic maps as long ago (in relative 'IT' terms) as 1979. Robinson (1976) reported on the 'revolution in cartography'. Indeed, a range of new techniques, including 3D views, spatial databases and automated generalised topography was examined by various workers throughout the late 1970's and early 1980's. The author added a geomorphological aspect involving the modelling of the Land's End Peninsula, Cornwall, UK, which could be examined in 3D perspective in order to trace well-documented ancient planation surfaces (Griffin and Gilmour 1981). All this work, using computers to manipulate maps, is of great relevance to the synthetic terrain modeller, as the scales being used are important according to what sort of landforms one might expect. Indeed, Ahnert's authoritative relational scale (see Figure 2.4) can be used as a good approximation when it comes to selecting scale and the desired area to be covered (generally known as AOR - or Area of Responsibility in mapping circles - Kennie (personal communication, 1987).

It has been seen how various non-academic bodies, particularly in the military, conceived requirements for synthesised terrain and how several attempts were made to satisfy this demand - not for synthesised terrain *per se* - but as a means of acquiring digital data cheaply, rapidly and in a desired format or with a particular set of characteristics. If digital data had been readily accessible with all these attributes then no doubt the MOD and defence organisations in other countries would have been satisfied with this.

In the 'academic world', however, such requirements are superseded by quite different requirements. These can be described collectively as *the need to understand the processes, agencies, chronological development and forms of the landscape.* This has been done - and still is being done - by workers in the various Earth Science fields, including geomorphology, hydrology, geology, physical geography, landscape classification, cartography, oceanography and other disciplines (it should be noted that geomorphology is part of geology in the US and elsewhere, but that it forms part of physical geography in the UK).

New technologies, such as sophisticated satellite mapping of earth resources and the rapid and massive increase of personal computing and mass communication, have added a new dimension to the information available to such workers, indeed this dimension was unimaginable to researchers chained to books and research papers in the libraries of the 1970s and before. As mentioned above, currently valuable work is being done in the field of GIS - a good summary of generalising spatial data and handling DEMs is (for example) given by researchers such as Heywood *et al* (1998), Hutchinson and Gallant (1998) , and Weibel and Dutton (1998). Finally photographs have been used as a medium to simulate terrain - mostly for land use studies (Stamp 1990), while Wherrett (1999, 2000) used the internet and the World Wide Web (WWW) to conduct studies of landscape preference based on a photographic medium.

Over the years, many attempts have been made to simulate terrain in order to try and reproduce or understand some facet of the natural processes that have created, and are still creating, the earth's surface. Such work is immeasurably eased by the use of powerful and accessible computers, with a host of application software to allow plotting and mapping of results, graphical output of statistics, 3D and other displays. The following paragraphs attempt to describe some of the main efforts at synthesising terrain (as opposed merely to recording existing terrain) using digital computers.

2.3.13 Geoscientific information technology - the Database

It is clear that synthesising digital models of the terrain is a relatively new area of research and therefore there are few workers examples and precedents on which to draw. Although some aspects of the DEM can still be processed manually (such as the data acquisition quoted in the last example), powerful information technology is normally required in order to manage, store, manipulate, transport, reformat and visualise the terrain data sets. Indeed, the whole field of synthesised terrain has grown out of the need to 'process' and establish cost-effective DTMs and DEMs based on real terrain, and terrain modelling generally would - these days - be unthinkable without computer assistance - and in particular - the database.

Cartography has also played its part, as has the developing application technology described in the preceding paragraphs under Geographical Information Systems technology and the various standards and formats used to present or display information to the user. Since the relational database management systems (or RDBMS) work on a 'row and column' method which is supported by the relational-entity calculus model (Date 1990). While this is fine for retrieving simple data (e.g. employee/payroll etc.) the row and column method is an inappropriate method of storing raster and vector information (Brown 1991). However, an RDBMS can be used to store information *about* raster (i.e. digital) formats. As GIS technology started to gain momentum as a 'discipline' in its own right in the 1980s (see for example Rhind and Mounsey 1989), it required database support to help with the sometimes vast volumes of digital data. The Oracle database, for example, has a spatial software module that allows the main database to process spatially-referenced data by means of one of the GIS products on the market, such as Intergraph or Formida (Oracle Corporation Marketing Literature 1998).

What is important, no matter the derivation, is that previously 'incompatible' types of data- spatially-referenced and non-spatial data - are now being linked to become parts of viable 'applications'. Thus a GIS user could (if the data sets were available) run a database query such as:

> ***Select all hospitals which have equipment types (A,B) from areas within the polygon defined by (A, B, C, D, E and F) and display at 1:50000 scale***

The query being processed relies on a mix of different datum types: map data, spatially-indexed data (such as the grid reference of hospitals) and non-spatial data (such as the medical equipment types which are 'attributes' of the hospital data sets, or alphanumeric data - Ware 1984). This is an old problem as far as IT and database workers are concerned. Spatial data sets (where gridded, vector or other types of formats prevail) can now therefore be linked with the familiar row-column structures and tables that constitute the relational entity model (Date 1994) without the difficult customised software that needed to be created by skilled 3GL and 4GL programmers during the 1980s.

Partly due to such technologies, GIS products are now regarded as a major technology area, with its own periodicals and products (Berhardsen 1992, Jones 1997, Burrough and McDonnell 1998, Heywood *et al* 1998). Database companies such as Oracle or Informix have therefore been obliged to produce customised software to allow spatial queries. GIS technology allows a 'different' way of perceiving the world, providing the correct data sets are available, and several authors have commented on the organisational changes that GIS technology has brought about (Dangermond 1989, Ratcliffe 1999). It is suggested that the database - with its various applications and display tools - is an important organisational element in the correct usage of GIS. Indeed, Oracle spatial data modules are now engineered to integrate with most off-the-shelf GIS products, including Formida, ArcInfo, and by ESRI and many others.

2.3.14 Computer and software models that synthesise terrain

Software models that create or synthesis terrain are relatively common on the web, or as 'shareware'. A typical example is 'Terrain Maker' (Jorgensen 1994), where plan views or 3D views are options as part of a 'terrain making' package. This bases terrain on islands and coastline, using colour for simulated elevation. The software appears to be purely 'mechanistic' in that there is no attempt at geomorphological integrity or realism and the purpose of the terrain appears to be as a 'target picture' for the POV software package (which itself is capable of significantly realistic 3D images). Figure 2.7 shows what can be achieved using Terrain Maker.

Other software exists which simulates some or all of a landscape. A sample of these packages has been inspected and includes systems such as HASP, MOSS and PANACEA (see Petrie and Kennie 1990). Also, in the paragraphs on web sites (see below) the mathematical and other factors have been listed. These packages are not included with 'serious' DTM construction and management packages based on real data, but are purely used to present or create some kind of synthesised landscape (or a particular part of one). It is interesting that none of the

Figure 2.7 Examples of fractal synthesised terrain (After Jorgensen).

authors of the software packages examined attempted to justify the terrain under the label of 'realistic' or 'geomorphologically-sensible'.

Other workers who have attempted to create terrain include the following who have examined terrain from a purely mathematical point of view, and indeed some surfaces have been 'passed off as synthesised terrain'. These have been described or created by Collins (1992), Fournier *et al* (1982), Peintgen and Saupe (1988), Prusinkiewicz and Lindenmayer (1990) and of course Mandelbrot (1982).

Workers (mostly non-geomorphologists but computer graphics specialists) who have attempted to create or render synthesised terrain include Dixon and Kirby (1994), who created 'artificial terrain', while erosion models were used by Kelley *et al* (1988), Marák *et al* (1997) and Beneš *et al* (1997). The latter (Beneš *et al* 1997) is an attempt to synthesise 3D terrain - again with a 'realistic' appearance, but for an computer graphics audience and the paper expresses little - if any - interest in geomorphological accuracy.

Musgrave *et al* (1989) wrote about the synthesis and rendering of eroded fractal terrain in the context of computer graphics, whereas Prusinkiewicz and Hammel (1993) considered a fractal model of mountains and rivers. Rhind (1992) considered spatial data handling in the geosciences - and touched upon the different ways of managing data and the different types of GIS user. He (indirectly) commented on the paucity of real 3D data sets while commenting on the potential size of the GIS market value. Gargantini (1992) bridged the gap between modelling 'natural objects' (using 'octrees') and the geosciences, while Belcher and Paradis (1992) touched on the mapping of 3D 'synthesised natural objects' and surfaces but without recognising them for their geomorphological value or identity. Kelley *et al* (1988) produced a particularly interesting paper on 'terrain simulation using a model of stream erosion' as it represents an attempt by computer graphics experts and geologists to combine and produce a 'deterministic' model. Fractals are not rejected, but are criticised for being only 'efficient' - not for being realistic. This is a view held by the author for many years - fractals have their place in geomorphological research but 'amplifying' a small structure into a vast landform assemblage through fractals alone is not rigorous enough. Indeed, the theme adopted by Kelley *et al* is entirely in accordance with the views of the author in this thesis and in the author's earlier works (Griffin 1987) - which was incidentally - published a year before Kelley's paper.

Finally, and perhaps most interesting of all, Pickover (1995) showed how to generate what he called Extraterrestrial Terrain, again for computer graphics applications. Some of the above have contributed to the web sites listed at the end of this chapter and in the appendices (particularly Marák).

2.3.15 The search for realism

Workers who have explored the concepts and philosophy of creating DEMs by artificial landscapes in order to produce 'geomorphologically viable' terrain or 'High Fidelity Landscapes' are relatively few. However, there are some workers in the field or in variations on the relationship between geomorphology and mathematics (Wolf 1984, Petrie and Kennie 1988, Wood 1996).

Another exception is provided by the author, who created a rapid method for simulating a simple runoff model (Griffin 1987), while there are few other workers who have looked at mathematical models to produce artificial landscapes other than at web sites (see below) or as part of classified defence projects (see the section on military work). There are many ways of synthesising terrain apart from using computer simulations. Although it is the range of IT methods that concerns this part of the thesis, it is also valuable to examine the other ways in which terrain can be synthesised - whether a description in a novel or a 'real' tract of landscape gardening. All these efforts are relevant as they show how the forerunners to synthesised terrain in the strict sense (i.e. before landscapes could be created by computer modelling) have been used throughout history. This part of the chapter also introduces the concepts of terrain classification and terrain evaluation in more detail.

As suggested above, the deliberate synthesis of terrain to produce DTMs tends to be a subject associated with computer graphics and modern Information Technology, and indeed this is the case as far as the thrust of this dissertation is concerned. Few workers have synthesised terrain unless this is to generalise about the morphology or genesis or development of a landform assemblage or a real area. This is not true 'terrain synthesis' in the sense that a complete artificial DTM is being deliberately created for some purpose, such as simulation.

However, having said this, many authors have produced works on generalising or creating terrain. Mathematical work, the motion picture industry and artistic efforts are discussed in the following sections, so this section is devoted to GIS exponents or earth scientists who have produced models or attempted to synthesise terrain - although not necessarily for the reasons of terrain synthesis undertaken in this thesis.

Weibel has produced a number of works on computer-assisted terrain generalisation, ranging from rule-based systems (1991) and becoming increasingly sophisticated (1992, 1995 and 1997). Weibel and Dutton (1998) produced virtually a definitive paper on generalising spatial data, with all its ramifications, and give a comprehensive reference list. Turner (1992) edited a general work on three-dimensional modelling with geoscientific information systems, and this work includes papers by contributors like Fisher and Wales (1992), who looked at solid modelling of 'geo-objects' (by which they mean geological structures). An interesting point is that GIS and solid modelling is one of those disciplines that transcends the boundaries of spatial modelling away from geospatial representations - into areas such as the modelling of bone tissue etc. (Gargantini 1992).

Some workers are 'on the edge' as it were, of true synthesised terrain, although as geomorphologists they tend to refer the work back to real areas for validation or justification, which is inherently reasonable. The work of Ahnert falls into this category. Although many geomorphologists have been using computer and mathematical models to research topics for many years (e.g. Kirkby 1969, Anderson 1988), Ahnert has spent considerable effort on modelling slopes, some of which are virtually 'synthesised' - although his aims do not coincide with the stated objectives of 'true' synthesised terrain outlined in this thesis. Ahnert has already been mentioned: he examined slopes as early as 1964, and produced works on computer models in 1977, 1987 and 1988, to choose but three recent and representative works. Some work has been carried out at Cranfield in the UK (Blackledge 1992) and working papers on synthesised terrain were produced by the MOD in the early 1990s, although no details have been discovered and the work has not been made available to the author. It is thought that this work helped generate the requirements for the DRA work described in this thesis (this is a case where the military and non-military fields once again overlap).

Some simulation 'terrain surfaces' have also been available during the 1990s (e.g. as flight simulators and arcade games) but these are either discounted as not being serious, documented work or are examined in the following sections (e.g. under Web sites).

Other work that does exist on the creation of synthesised terrain is multidisciplinary. Indeed, apart from war maps and the history of art, synthesised terrain work is characterised by its relative modernity and associations with modern digital computers, since the exposure of scientists and technologists to powerful computing capability (and *vice versa*) is a relatively recent phenomenon (DeMers 2000). However, before reviewing work carried out since the 'dawn of the age of the computer', it would be remiss if some other, 'pre-IT age' work was not first examined in this chapter, as strictly speaking, synthesised terrain although not a subset of Information Technology, requires relatively sophisticated IT resources to be created, managed and presented. For example, synthesised terrain - sometimes in hand-drawn 'wireframe' 3D diagrams - can be used to illustrate any point - the 3D art and pictures of imaginary landscapes in a Norwegian book about sailing and navigation (Aschehoug and Co. 1979) provides a good example that has already been mentioned.

2.3.16 Terrain Evaluation: non-military

Terrain Evaluation is also important in the earth sciences and is not, of course, just a military based topic, although it has been introduced earlier in this chapter under a 'military' heading. As a subject it is not really concerned with synthesised terrain models, but like terrain modelling generally, many of the same techniques can be applied. This subject has been introduced in chapter one as underpinning one of the chief methods of collecting data for synthesising real world locations, by means of terrain classification. Speight (1973, 1974) has produced some thorough work on a parametric approach to landform regions, in which he summarised earlier literature and suggested methods of recognising landform patterns, which he classified as:

- Regions
- Recurrent Landscape patterns

- Simple Land Systems
- Landform Systems
- Relief Units
- Landscapes

The works of authors such as Speight (1973, 1974) and Mitchell (1991) were also used as 'controls' in case any issues arose.

2.3.17 The 'Quantitative Revolution' in Geography and the use of models

There is a general belief that a so-called 'quantitative revolution' in physical Geography took place in the 1960s and beyond which left its mark - it was the trend of the times to explain form and process by statistical, diagrammatic and other numerate techniques. Undoubtedly such a shift did take place - whether it was a 'revolution' is not for the author to comment - but it is clear that many workers in the UK and around the world started to adopt a more statistically-oriented and generally more numerate approach to their subjects. This took advantage of the early electronic calculators and computers in UK (and other) universities. The term 'revolution' may have been over-stressed in some quarters, and while it did not undermine the brilliant theoretical work of authors like Wooldridge and Linton (1955) - as may have been feared - it did help to produce a more rigorous approach to geomorphology (see, for example, Chorley 1969). Indeed, some workers were responsive to the 'new wave': for example (Board 1967) suggested the use of Maps as Models, while Chorley and Haggett (1967) produced an authoritative work on Models in Geography, and other workers produced what became 'pioneering' efforts (e.g. Davies and McCullagh (1975), Sprunt (1970, 1975)).

(. From personal experience, the author was an undergraduate student during this time (1971 - 1974), and recalls the enthusiasm with which electronic calculators, statistical worksheets and Hollerith cards were handed out in almost every practical study period during a geography/geology degree course.

Indeed, geomorphology has always been a 'numerate' science and there are many examples prior to 1960 where mathematical approaches were used (e.g. Horton (1945), Strahler (1957) and others working pre-1960). It could be argued that the increasingly numerate and computer-oriented skills-base of students and academics alike led to the current highly technical GIS and technology-driven Earth Science courses (and their derivatives) in Universities around the UK and elsewhere. This in turn led to the creation and understanding of the concepts that we now take for granted in the field of digital terrain modelling.

As far as the search for previous synthesised terrain work is concerned, attempts at describing landscapes by means of synthetic methods led initially to more rigorous 'hardware models'. Experiments involving the mixture and pouring of a plaster-of-Paris base to simulate glacier movement (Lewis 1949) is one typical example. Elsewhere, cartography and geography students (the author among them) were encouraged to use their imagination, on occasion, in conjunction with their cartographic and geomorphological skills, to draw imaginary islands at 1:25000 scale, as exercises in the use of stencils, pens, and cartographic techniques. This, in the author's experience, turned out to be a remarkably difficult exercise, since the 'end product', albeit with lovingly drawn coastline, contours and settlements, was in most cases only really a transposition of an area familiar to the artist, and in many cases parts of what resembled the North Downs or the Brecon Beacons were carefully transposed into an island suspiciously reminiscent of the Isle of Wight. In other words, it was difficult to create landscapes other than those experienced by the students unless one was prepared to sacrifice geomorphological integrity: the 'blank sheet' approach to synthesised terrain is difficult.

Finally, IT and quantitative methods have affected cartography in their turn (Muller 1991). This is not just reflected by the many GIS products and the UK Ordnance Survey's range of commercially available digital maps, but in developments such as cartographic databases (Frank 1991), computer-assisted map design (Rase 1991) and many other advances in cartography (see Muller (1991) for a general work at a time when cartographers were adopting IT capabilities both seriously and competently).

2.4 Other work

Apart from the military antecedents of the synthesised terrain research and the earth science background which underpins the theory in this thesis, there is a third area where workers have attempted to create artificial landscapes, but which attempts do not really fall into a 'military' or an 'earth science' backdrop. The following paragraphs conclude the chapter with some interesting examples where synthesised terrain - in a very broad sense - is examined.

2.4.1 Early work on synthesised terrain creation: Artists and Landscape Gardeners

For centuries mankind has attempted to map and understand the landscape that forms the surface of the world that surrounds him, and many comprehensive works exist on the early geographers and cartographers, and on the history of map-making and its impact on geography up to recent times (Raisz 1938, Robinson 1952, Board 1967). The following paragraphs are not intended to give an exhaustive history of map-making and the origins of cartography; the intention is merely to set the context with some examples demonstrating that maps can have an element of perception in their production.

Hecataeus, a Greek who lived during the mid-fifth century BC, produced two maps; one of Europe and one of Asia (including North Africa) and whereas later writers, such as Herodotus, ridiculed this work they still copied some of the information (Dean-Jones 1998). As mariners completed successful circumnavigation voyages, more accurate maps of the globe began to emerge in the 15th Century, until we have tactical maps of the progress of the Spanish Armada in use by Drake and the famous English mariners throughout the sea battles of 1588 (Thomas 1988). Throughout history, landscapes were sometimes created artificially - that is - without reference to what was actually outside an artist's studio - in order to provide images, such (for example) as a 'bird's eye view' of a tract of land. Imaginary (i.e. synthesised) landscapes were used as decorations for chimneys in 18th Century London and imaginary 'landskapes' *(sic)* were commonplace as essential parts of theatre sets in Hogarth's London (Uglow 1997).

Indeed, up to the last few hundred years landscapes have been presented as elevated viewpoint maps - effectively '2D aerial views'. These representations of the world, or even of well-known coastlines such as Great Britain, were a mixture of conjecture and realism, resulting in many strange but vaguely familiar forms before, for example, the outline of coasts we have come to take for granted today were more accurate (Blakemore 1980). These renderings would be produced as maps, or would be done at the actual perceived scale of the landscape itself to produce 'realism', or to produce some desired artistic or aesthetic effect. Attempts at producing relief through hachuring was commonplace by the 18th century - the Scottish maps of General Wade are a good example (Glover 1977). Of course, these were not synthesised landscapes *sensu stricto,* but an element of imagination and synthesis crept in when the facts were not available - Martin Behaim's Globe of the World, drawn in 1492, was produced before Columbus reported on his discoveries, and there are similar examples from this period of history (Williams 1994).

Many renaissance artists clearly drew on imagination for 'background' landscapes, even though they might have their human subjects in the studio. For example, Benozzo Gozzoli (1421 - 1487) painted strange rock formations in the *Journey of the Magi* (Copplestone and Myers 1969). Other Renaissance masters painted in studios and 'invented' landscapes when they had to (Crystal 1998), but it was not until the driving force of classicism and the Dutch School of art in the 17th century that artists started to look at the world around them with 'fresh eyes'. This resulted in accurate representations (or at least interpretations) of the landscape, which were characterised by 'beauty spots'.

The works of Gainsborough, Turner, Samuel Palmer, Thomas Girtin and the illustrator Thomas Bewick (see the 'AA British Book of the Countryside' 1973) underline this trend, while other painters, such as Courbet, strove for 'attractive views', while Turner was moved by the beauty of the Italian landscape (Chilvers 1992). Interestingly, this new realism relied on a form of synthesised presentation: Thomas Robins the Elder (1716 - 1770) painted what he imagined was an aerial view of Charlton, near Cheltenham, England in the mid 18th century. His detailed painting is among one of the earliest perspective views, but it is also interesting in that he was visualising the town - he had no means of actually observing it. As a result, the slopes are exaggerated by 4 or 5 times their actual angle for effect. This is a phenomenon that will be dealt with later in the thesis as it has importance to the author's synthesised maps.

Finally, a form of synthesis was enacted on the landscape itself by masters such as Capability Brown (1716 - 1783), who used informal designs as a foil to the strict geometry of the school of French landscape gardening. To quote the Illustrated Encyclopaedia of Britain (Readers' Digest 1995): *"he . . .went to great lengths to create seemingly natural effects that blended in with the surrounding countryside".* Indeed, the term 'landscape gardening' was coined by Humphrey Repton (1752-1818), who invented the term to express his theory that the art requires "the united powers of the landscape painter and the practical gardener." Because he was keen for his employers to see what he proposed to do, Repton devised an ingenious system of sliding panels. Each panel showed a park or garden in its original condition before Repton's proposed improvements; an overlay would be lifted in place to reveal the altered vista - in this sense Repton was showing a 'before and after' effect. In the text of his book, Repton (1816), he discussed the relationship between landscape gardening and architecture in chapters on colour, interiors, prospects, water, fences and other subjects.

2.4.2 Hardware models: Other

There are other Examples of military hardware models have already been described earlier in this chapter. There are other hardware models which are worth mentioning in the following paragraphs.

Some hardware models are fairly obvious. When the author used candles burning in a large block of wax to model the relationship between precipitation runoff and weathering pit development (Griffin 1977), this was a crude example of a hardware model to synthesise some aspect of the terrain (in this case at a very detailed level). However, some other models are less tenuous - the description of various laboratory models of ice flow (to model glaciation) cannot be said to create 'synthesised terrain' (Embleton and King 1971), nor can any of the numerous laboratory experiments on stream flow (Knighton 1998).

2.4.3 Science Fiction: Hardware Models and Fiction

There have been many scale hardware models of artificial terrain constructed for television and Science-Fiction films, particularly in the 1960s for Independent TV puppet shows ('Space Patrol', Gerry Anderson productions such as 'Thunderbirds' etc.) and 'drama' series such as 'Dr. Who' and 'Star Trek'. Indeed several excellent photos of model synthetic landscapes (i.e. they have no deliberate real-world analogue) are to found in works such as 'Dr Who - 25 Glorious Years' (Haining 1988) and 'Dr Who: 30 years of time travel' (Rigelsford 1995).

Indeed, descriptions of synthetic landscapes in various environments are to be found in modern Sci-Fi literature, including the landscapes of the soul and the mind in 'Feersum Enjiin' (Banks 1993) and various descriptions of exotic (and imaginary) planetary landscapes in the fictional 'Neutronium Alchemist' trilogy (Hamilton 1997). Terrain synthesis (not simulation but actual man-made terrain) is dealt with in a humorous science fiction work 'Hitchhikers Guide to the Galaxy' (Adams 1983) and in the novel 'Strata' by Terry Pratchett (1998), while 'terraforming' (the deliberate creation of earth-type planets from hostile alien environments) is a common theme (Hamilton 1997) and even appears as the main plot in one of the Star Trek motion pictures. The fictional 'terraforming' of Mars is discussed by Robinson (1994) in a series of works, while the late Frank Herbert wrote about the multiple transformation of the fictional planet Dune from desert to fertility and back again in the five 'Dune' novels (see Herbert 1976). Interestingly, Herbert shares, with J.R.R. Tolkein (who imagined beautifully detailed fantasy landscapes in his novels (e.g. Tolkein 1977) an acute observation of the environment and landscape - it is suggested that these latter two authors certainly had an eye for landscapes even if they were professional writers - one may well imagine that both were at least aware of the delicate balance of ecology and geomorphological form and process at an intuitive - if not intellectual - level. Incidentally, there is a web site devoted to detailed 3D views of Tolkien's carefully described 'Middle Earth' landscape (see ***http://www.geocities.com/TimesSquare/Alley/1506/memap.htm***), while a query on the AOL.COM internet search engine using the string '3D maps' revealed over 1900 'hits' - the example above amongst them.

Finally, one must question just how far one can take a review of 'literature' into synthesised terrain in all its forms. There are many examples even from the music business, where the presentation of record album covers and CD covers can often show 'fantasy landscapes'. Some examples are given in Thorgesen and Powell (1999) and a recent CD cover (Radiohead, *Kid A*, Sony Music Corporation 2000) has a pull-out of 'fantasy landscapes'. Clearly these are just examples and the literature search must have boundaries - the crucial point is that almost no example in any genre purports to show geomorphologically -viable realism.

2.4.4 Science Fiction: Software and Photographic Models

By the 1970s some computer-generated terrain had been produced for visual reasons (e.g. see Hanning 1988). For example, the title sequence to the early episodes of the BBC series *'Blake's 7'* included a 'Head up Display' or HUD of a spaceship climbing above an alien terrain into orbit. Interestingly, this graphic sequence compares favourably with the HUD available to contemporary Royal Air Force Tornado pilots and navigators, giving information such as attitude, position, speed and external tactical information. To this end, some work has been done to produce fictitious terrain as computer-based cinematic special effects for the Motion Picture industry (e.g. the synthesised terrain landing display for the spaceship *Nostramo* in the film *Alien*, carried out and documented by Sutcliffe 1981), for general computer graphics (Newman and Sproull 1979) and for extensions of the fractal-Brownian motion mathematics applications popularised by Mandelbrot and his many co-workers from the late 1970s onwards (Mandelbrot 1977, 1982).

These are often interesting in their own right, but in almost every case the desired effect was to produce 'spectacular' or even 'alien' landscapes (Hanning: personal communication 1988), and therefore the validity and geomorphological viability of such efforts would be either ignored as 'irrelevant' or simply not called into question. Indeed, making an 'alien' landscape is, by definition, deliberately not to create recognisable or even plausible 'earth' terrain, but to err on the side of the improbable, the spectacular and the exotic. Returning to Ridley Scott's *Alien*, the landscape created in this film (1979) was, for example, swirling with mist and few specific landforms in the conventional sense could be identified, even in the spaceship landing sequence (Sutcliffe 1981).

Sometimes terrain is synthesised as a background for a documentary. In the UK BBC series 'Walking with Dinosaurs' (BBC Productions 1998) a 'speeded up' representation of millions of years of erosion, mountain uplift, climate change and marine inundation effects is done over a few seconds to illustrate the radical difference between present-day landscape conditions and Cretaceous and Jurassic landscapes. Since the programme makers are unlikely to have had accurate topographical maps for such a sequence, they have used a variety of film and animation techniques to 'cut and paste' distant mountain ranges apparently rising and falling in a matter of moments, with considerable success. This is a good example of where realistic-seeming terrain has been synthesised through animation and film techniques. Absurd, strangely coloured or 'unrecognisable' landscape - even for long distant geological periods - would have probably jarred the sensibilities of most viewers, even those without an interest in terrain.

From a psychological point of view, It is probably fair to assert that the human mind has a conceptual model of what is 'reasonable' terrain - one might expect spectacular cliffs and mountains but not overhangs (which are rare in nature apart from on a small scale) or improbable scenery such as hills tapering at the base - Wherrett (1999, 2000) examines similar concepts in her work. Similarly, rivers do not run uphill and coloration tends to be within the reddish-yellow-brown part of the electromagnetic spectrum - a violent blue or purple landscape would be disturbing to most people. These may seem obvious points but they are important in a general sense.

2.5 Web sites: synthesised terrain and other references

This final part of the chapter reports on some web sites which have been found by searches or by personal correspondence. Web sites are 'places' on the WWW (World Wide Web) or the internet - where virtually anyone with the resources can publish material on virtually any topic (Gralla 1999). Although they are prone to disappear and therefore have an ephemeral nature it was felt that a small sample should be obtained for completeness, to demonstrate the synthesised terrain visible by means of the web. These are summarised in full in Appendix D, but some abbreviated examples are given below (this is also necessary for continuity with terms etc. used later on in this thesis) in the following paragraphs. Some real-terrain examples are also given by way of comparison.

- **http://wien.ac.at/studentwork/CESCG97/marak/node3.html**

This site ('owned' by Ivo Marák) looks at synthesised terrain surfaces from the point of view of mathematical modelling, although no geomorphologically-viability is suggested.

- **http://wien.ac.at/studentwork/CESCG97/marak/node6.html**

This is a similar site from the same source, dealing with the creation of mountains and rivers.

- **http://www.metavr.com/97F-SIW-107.html**

This web site is dedicated to the Rapid Terrain Visualisation (RTV) programme that is designed to provide Digital Terrain Data (DTD) to military units for intelligence and analysis, mission planning, and course of action analysis. This enhances real terrain but it is not clear from the web site how much 'synthetic' terrain is involved, nor is there any geomorphological validation.

- **http://www.metavr.com/reFrameIndex.html?http://www.metavr.com/mout-complete.html**

This web site allows the user to access several options and view a number of good quality military-based synthesised terrain views and simulation products.

- **http://www.mors.org/67morss/wg29.html**

Searching for 'Natick' on the web produces some interesting results. The US Army are still carrying out Terrain-related work, and there are several web sites related to synthetic terrain, some of which refer to the SNE system (see previous website). All appear to involve military simulations. However, none of the papers or websites gave any indication of validation or geomorphologically-viable terrain, except to point out that the terrain simulations were 'realistic'.

- **http://www.computer.org/conferences/ais94/marty/paper.html**

This web site, from the US military, discusses synthesising terrain for route planning. Route planning is another area that is frequently associated with automatically guided vehicles (AGVs) and it has been mentioned briefly in the work done on the UMV project (Griffin 1986). Some work has been done in this area but it tends to be related to an industrial project (see for example Huss and Weber 1983)

- **http://www.oslo.sintef.no/wavelets**

This site, based on the University of Oslo in Norway, is concerned with using Wavelets to create surfaces. It is a good source for the theory and application of Wavelets (which are considered in chapter three) and there are many colourful 'surfaces', but again, although 'realism' is discussed in the web site for flight simulators, no geomorphological viability is apparent. Written references on wavelets related to this site have been produced by Floater and Quak (1998, 1999).

- **http://www.multimania.com/bianco/**

This web site (in Italian), has been created by Luc Bianco, claims to make a system called Terragan, which produces realistic-looking terrain which a 'photographic' bias (in other words some real-world light and texture effects are included, such as the relative strength and position of the sun for terrain shadow effects). The text does not reference any geomorphological validation of the results, which are created using fractals and a number of PC-based GUI (windows).

- **http://www.ericjorgensen.com/html/tm.htm (Terrain Maker)**

One may download a product called Terrain Maker from the web site **http://www.ericjorgensen.com/html/tm.htm**. This is a crudely-coloured but relatively effective synthesised terrain system, downloadable as a software package which uses POVRAY (a 3D perspective tool discussed elsewhere in this thesis) for display purposes, and claimed to be a 'landscape editor'. Although there are no apparent geomorphological qualifications, the author of Terrain Maker claims that 'natural looking' terrain can be synthesised. Indeed, 3D views with different heights and colours can be created quite easily using a simple GUI. Terrain Maker is interesting in that 'sea level' can be altered so that the 3D view can be of a simulated inland region, it can have a coastline of sorts, or it can be an archipelago. However, the geomorphological validity of such models are questionable.

- **http://graphics.stanford.EDU/~liyiwei/project/texture/**

This project from Stanford in the USA concentrates on texture in synthesised terrain. The website states that "Texture is a ubiquitous visual experience. These textures can be obtained from a variety of sources such as hand-drawn pictures or scanned photographs". A reference paper is given as produced by Li-Yi Wei and Levoy (2000).

For comparative purposes there are the following web sites:

- **http://www.ordsvy.gov.uk/**

This is to show a contrasting viewpoint to synthesised terrain - this is the UK Ordnance Survey's website. It does not deal with synthesised terrain at all, but it gives the visitor to the site some idea of the range and high cost of products.

- **http://graphics.lcs.mit.edu/~seth/pubs/taskforce/paragraph3_3_0_0_2.html**

Thomson Training and Simulation (a subsidiary of Thomson) has developed a new generation of machines for image synthesis. A new *polygon engine* was built to allow the user to view collections of thousands of non-convex polygons with holes at interactive rates. In addition, a fully dynamic algorithm for constructing Delaunay triangulations was developed, which runs in real-time on the new machine. Many of the underlying ideas were borrowed from the recent work on randomised algorithms in computational geometry. In particular, the algorithm uses a hierarchical representation, the so-called Delaunay tree based on the work of Buttenfield and McMaster (1991), Boissonnat and Geiger (1993), Boissonnat and Teillaud (1993), Asano and Kimura (1995) and Bouma *et al* (1995), with contributions from Brost and Goldberg (1996). This resulted in a project to construct a terrain in real-time and automatically to adapt the database to the specifications of the graphics device as well as to the distance of the observer from the terrain. However no synthesised terrain is represented.

- **http://www.3dillc.com/rem-lidar.html**

and

- **http://www.lasermaps.com/**

are both websites typical of the detailed DEM and general terrain mapping that can be carried out by the Lidar or LIDAR (Light Detection and Ranging) system. An internet search on the term 'Lidar' will reveal many returns, although most are involved with atmospheric research and not all are terrain mapping. However Lidar techniques are becoming more important and may eventually affect the price of DTMs and DEMs so that the price advantage of synthesised terrain is offset or even nullified. However this is probably some way off in the future, as Lidar technology still requires an aircraft or space vehicle platform.

To summarise; Web sites are ephemeral and do not have the same 'quality control' or vetting procedures that ensures the good standard of papers in learned journals or scientific text books. This is discussed in more detail in Appendix D.

CHAPTER THREE : METHODS, REQUIREMENTS AND TERMS OF REFERENCE FOR TERRAIN SYNTHESIS TECHNOLOGY

Chapter Three

Methods, Requirements and Terms of Reference for Terrain Synthesis Technology

3.0 BACKGROUND AND HIGH LEVEL VIEW

This chapter identifies and reviews the theoretical and practical **methods** of synthesising terrain, from the early days of the research in the late 1970s through to the more advanced theoretical base and sophisticated computer techniques available to the author in the 1990s. These methods are introduced and their relative merits discussed according to theoretical and actual requirements. When appropriate, they are also compared (or contrasted) with each other and with the methods of collecting real data. The various concepts of scale, resolution, accuracy, and terrain classification (or evaluation) are also discussed when relevant, along with other fundamental terms, concepts and techniques that must be identified and understood in order to make sense of the intrinsic nature and value of synthesised terrain.

One important attribute of the methods during the later, more advanced stages of the research (from 1994 onwards) is that they can - in theory - be used in isolation or in a combination (usually with a two or three-phase process) of methods, especially if relatively sophisticated results are sought. This led to the software program called Geoforma, which represents the most developed composite modelling tools used by (and generated by) the research.

This chapter also examines the reasoning behind wishing to synthesise terrain, and the value attached to such activities in different areas of utilisation. This refers to the 'requirements' placed on the author by MOD sponsors and other commercial agencies to produce synthesised terrain. Although this may sound like a far cry from 'free academic research', the outcome probably would have been similar had the work been sponsored by a university, with the obvious exception that the synthesised terrain products were to be used in actual 'war gaming' and simulation purposes in the interests of UK and NATO security. Therefore some of the requirements were somewhat constrained by outside agencies, but there were two factors which offset this:

- The requirements encouraged geomorphological research in order to increase the credibility of the project and the validity of the synthesised terrain products

- The requirements placed a kind of discipline or rigour upon the author (and others in the project team), which - although it was culturally demanding - had the benefit of requesting frequent progress reports and setting deadlines for products. This is not to suggest that the academic world is in any way less rigorous, quite the contrary - it merely demonstrates that the requirements of a commercial, fixed-price contract had to be satisfied, and that the geomorphological research was a part of this. Happily the research produced successful DTMs, maps and other products, as this later stage in the research demonstrates (This is summed up in New Scientist 1997, September 7th, page 20).

Finally, the combination of the various methods - represented as algorithms - into a the software suite known as Geoforma, is also described, although it must be pointed out that this was the pinnacle of the research, and much work on dead-ends and unhelpful areas took place before the 'correct' methods (in this case the methods that suited the research) were identified.

3.1 How can Terrain be synthesised?

3.1.1 High-level Methods

Each 'high level method' lays out the broad or general 'rules' or requirements for synthesising terrain. The systems or software life-cycle should also be considered here as it is a component of most methods or systems in Information Technology (IT) - see Figure 3.1. Indeed, the processes used in the synthesis of terrain, as described throughout this thesis, mirror many of the so-called methodologies in the Software industry such as SSADM (Structured Systems Analysis and Design Method) or RAD (Rapid Analysis and Development), in that logical models are built, phases or stages are used (with iteration where necessary) and a rapid 'first-cut' approach may be taken to give the users an idea of the eventual 'product' (SSADM handbook 1986). In the final analysis, Object -oriented techniques were chosen as this was convenient to the experience of the author and the 'team' helping the author with peripheral tasks. The first-cut is not unlike an aeroplane designer building a scaled-down flying model or static model for the benefit of his customers - the audience will get a good idea what the aircraft could look like, and any revolutionary features may be immediately obvious.

3.1.2 Algorithms

An algorithm is defined as a set of instructions which together form a script or pathway towards the design, implementation or conception of a goal. In IT terms, an algorithm is the plain-language description of a software module. The algorithm is the 'blueprint' of a software

- **Pre-feasibility-feasibility studies (consultancy) + ITT**
- **Design - Requirements - Iteration (+ Architecture)**
- **Algorithm Design and choice of tools/products**
- **Detailed Design and Module Build**
- **Module test, Integration and overall integration**
- **Testing and acceptance**
- **Training, sign-off and delivery (SAT,FAT,CAT)**
- **Support and post-implementation maintenance**

Key

CAT = Customer Acceptance Test

FAT = Factory Acceptance Test

SAT = Systems Acceptance Test

ITT = Invitation to Tender

Figure 3.1 Software/Systems Life Cycle

module or program (an algorithm is defined in the Digital Dictionary (Marotta 1986) as 'a set of well defined processes for the solution of a problem using a limited number of steps'. This, of course, is in the context of software and IT).

3.1.3 Software and Program Design and Implementation

Having reduced the requirements to algorithmic form, it is then possible, with the correct knowledge, training and development facilities, to build a software model (or series of program modules) to carry out the instructions in a computer. Essentially, synthesised terrain is very much a visual subject, and the user would expect to see maps, diagrams or perspective views of the terrain models being constructed. Fortunately, there are many commercial off-the-shelf (COTS) GIS products available to the terrain modeller, whereas in the past (in the 1970s for example), apparently simple routines like contour plotting or 3D views had to be written in third-generation programming languages (3GLs -see Appendix D) from first principles (see Gilmour and Griffin 1979, 1980(a), 1980(b)). Now such 'luxuries' are - often via APIs (Application Programming Interfaces) of varying sophistication - among the standard modules of many GIS systems. The synthesised terrain software described in this thesis was written deliberately to interface with one or more GIS systems, either by means of indirect file transfer or through direct interfaces such as C and C++ modules, SQL if a relational database is connected and in some cases whatever API was offered by the GIS tool.

The generic name for the Microsoft NT and Windows-based software (written in FORTRAN, C and C++) has already been mentioned: this is Geoforma, named because of the author's original stream valley erosional programs were called GEOFORM (earlier GEOMIX, Griffin (1987)). Geoforma comprises a number of modules and which are identified when required. A schematic of Geoforma, and the processes

GeoForma:SyntheticTerrain Generator (software suite)

Figure 3.2 Geoforma - demonstration landscape

described below is shown in a sequence of diagrams. Figure 3.2 shows the kind of 'bare' landscape that can be created by Geoforma. Figures 3.3 and 3.4 indicate the landscape attributes handled by Geoforma - these attributes are explained in greater detail throughout the thesis. By way of contrast, Figure 3.5 shows a traditional view of the methods of data capture. Geoforma and its functionality is described in greater detail in the paragraphs below.

3.1.4 Cartesian Axis system

It should be pointed out that, unless stated otherwise, the research work was obliged to utilise the 'aeronautical' right-handed Cartesian (x,y,z) axis co-ordinate system. This is where the x-axis corresponds to north-south on a map, the y-axis corresponds to east-west and the z-axis is vertical (up-down). Some variants have -z <u>upward</u> from a (0,0,0) origin, as the altitude of an aircraft is of understandable concern to the pilot, and therefore the negative z is employed. However the negative z condition was removed wherever possible in this research to avoid further confusion. The adoption of this 'right-handed' set did occasionally cause problems, but it is standard procedure in the military/aeronautical environment in which much of the research was undertaken - see for example Blakelock (1965) and Britting (1974).

Finally, in some places in this thesis (notably in chapter three and five) where control envelopes, super-ellipsoids and other techniques are described, the axis system may be changed for ease of computation (so, for example, the Z axis may be exchanged with the Y axis). This was felt to be unavoidable as it allowed the computation to use established methods and theory without having to transpose the axis system with perhaps inevitable cross-checking and possible mistakes occurring. Therefore, any transposition is done prior to storage and display of the DEM, where the so-called 'right-handed' (x,y,z) system described above is utilised.

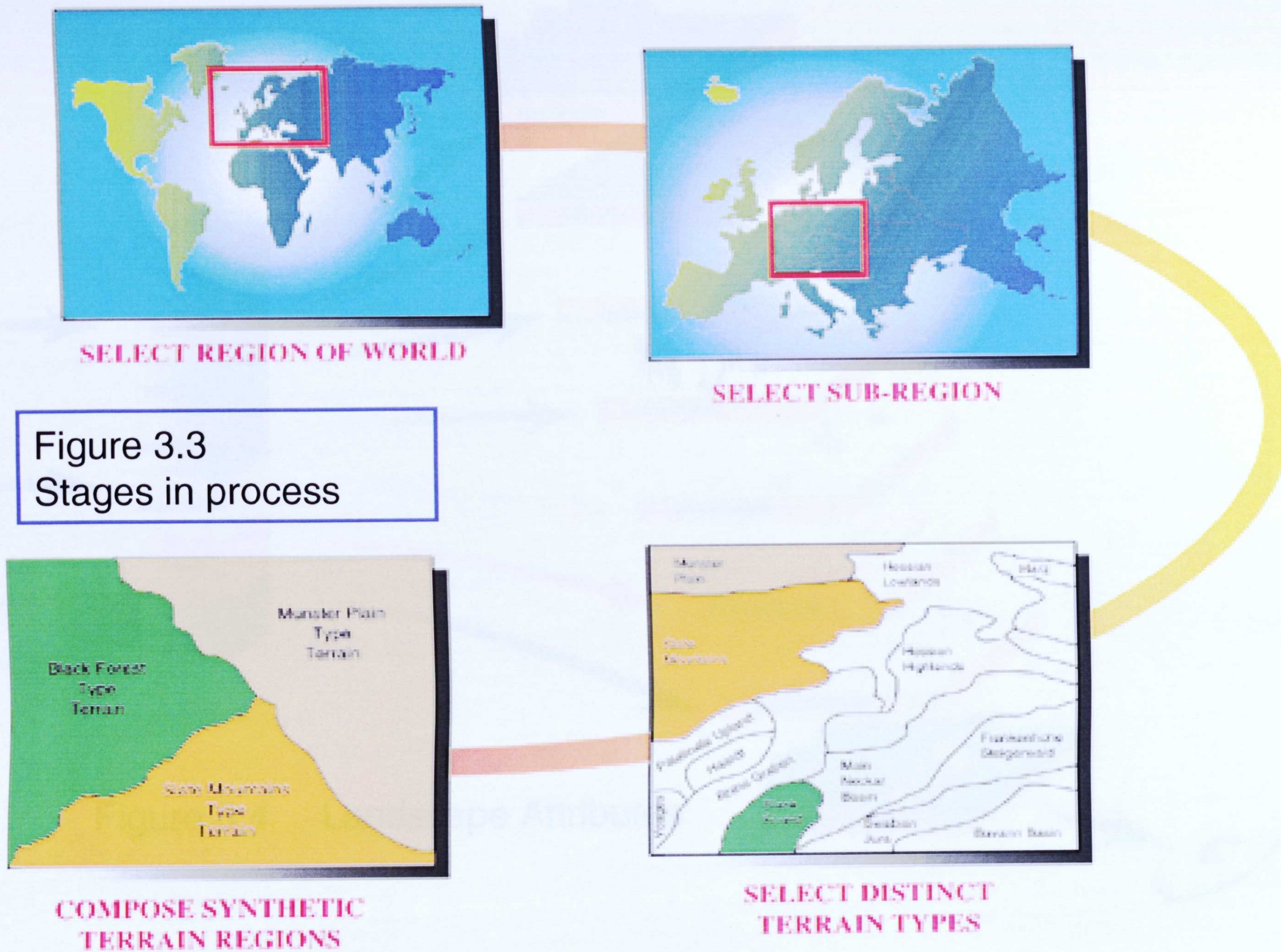


Figure 3.3
Stages in process

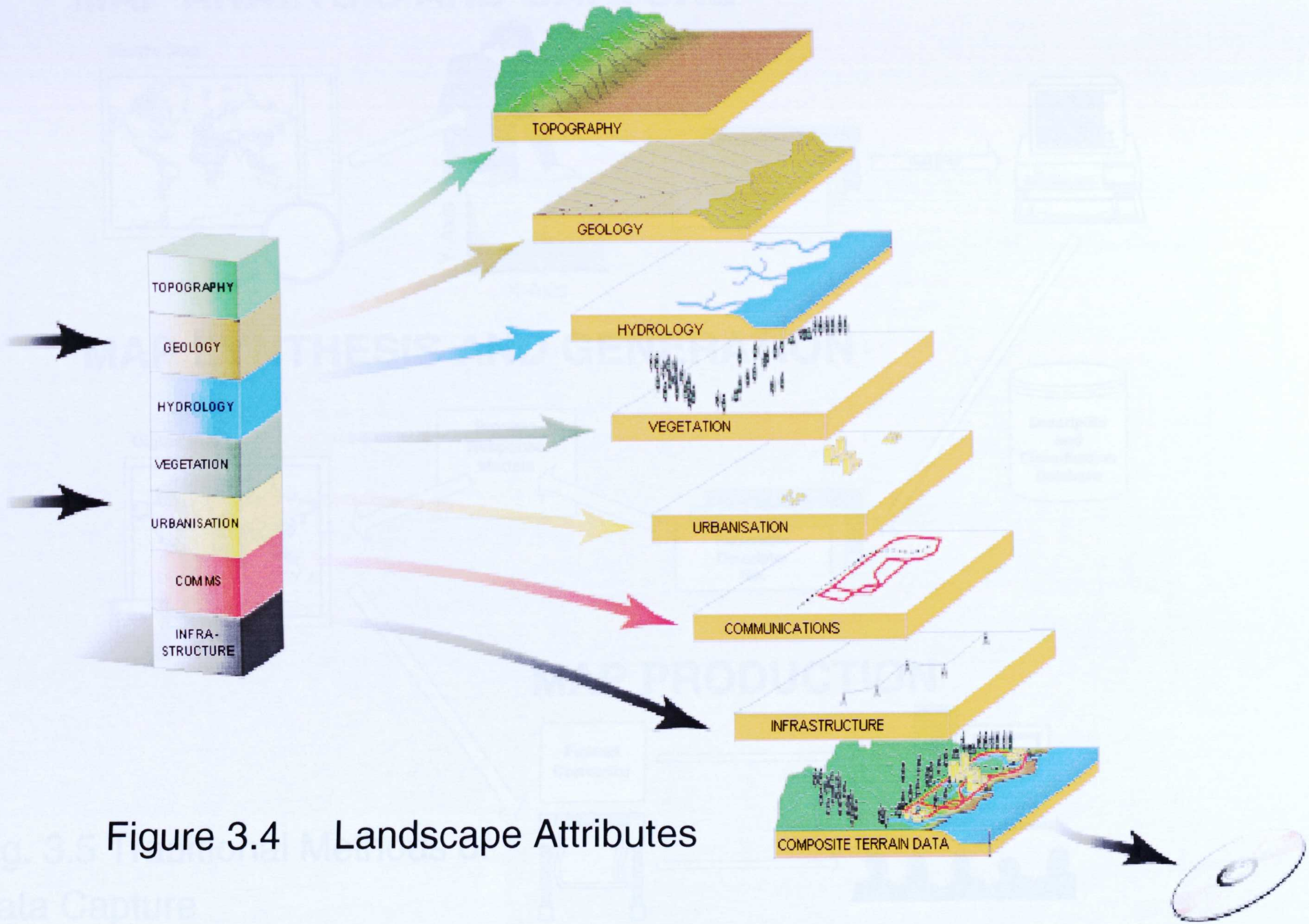


Figure 3.4 Landscape Attributes

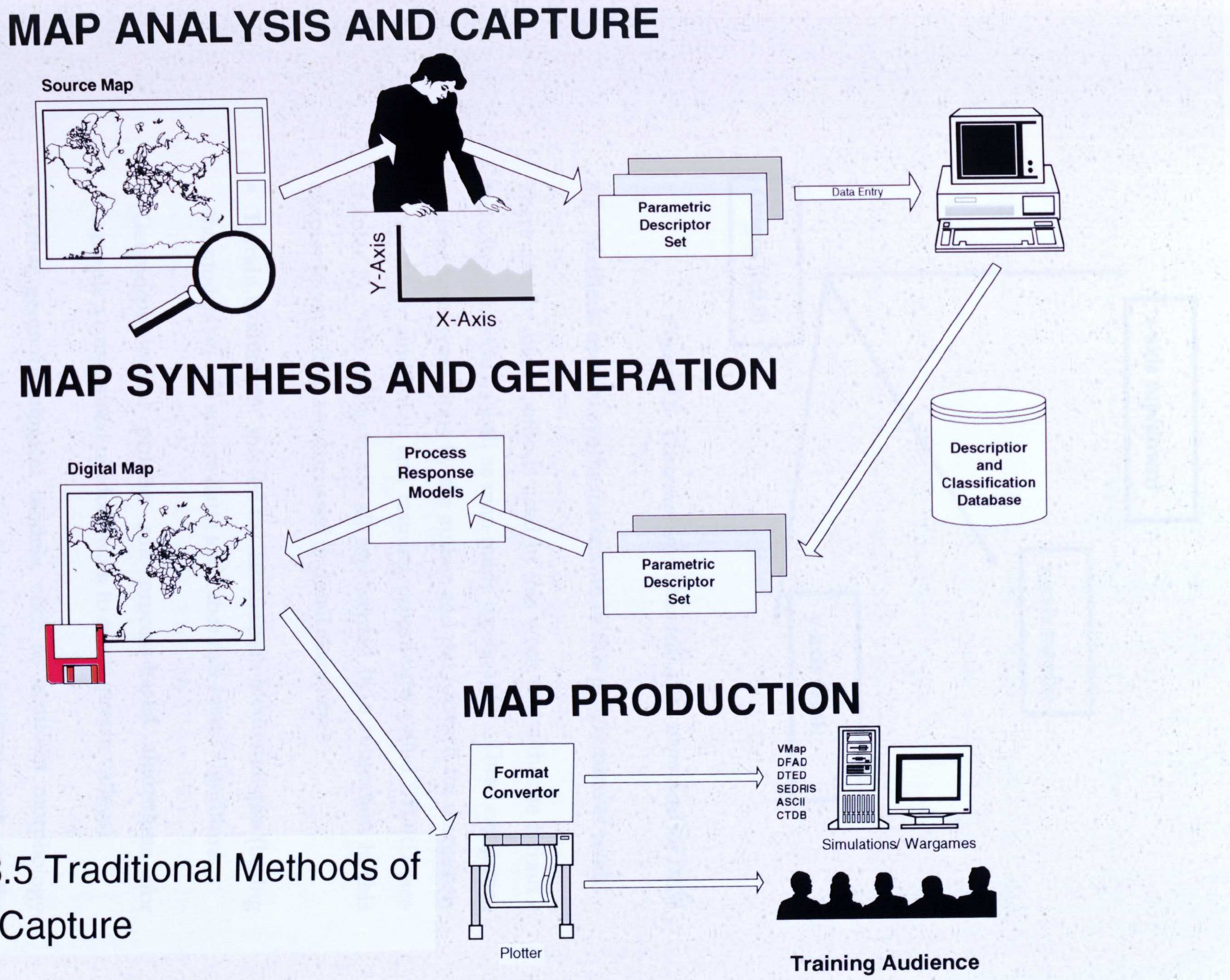


Fig. 3.5 Traditional Methods of Data Capture

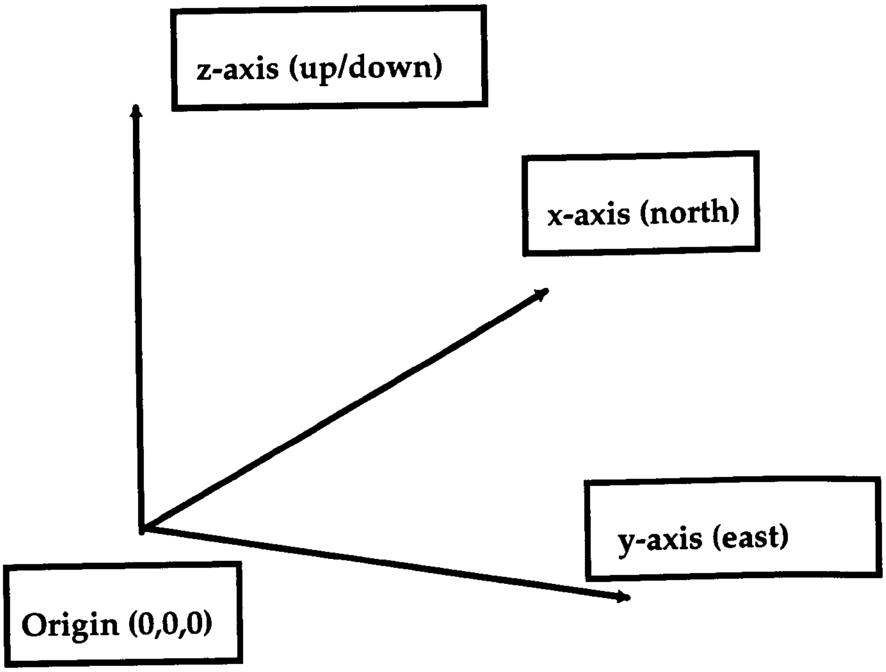


Figure 3.6 Cartesian (right-handed) axis system used for DEM

3.2 Methods used to synthesise terrain in this programme of work

There are six main methods used in this work to synthesise terrain - including physical as well as man-made topography. These categories evolved from work done by the author and put forward for discussion for an Army simulation and training programme called STDRD (see chapter 2). The methods are all represented by a subsection in this chapter (even if they are discussed in detail elsewhere):

- **Terrain Evaluation**: this led to Classification Methodologies (basing the models on real source data) and other rule-based algorithms

- **Geomorphological process and process-based algorithms** (for example a constrained random-walk to create stream valleys)

- **Other geomorphological models**, such as landform morphology imitation (used occasionally for detailed features such as the modelling of tors, for example)

- **Fractals**

- **Other mathematical methods:** Fourier Analysis, Super Quadric methods and others

This chapter concentrates on terrain evaluation and classification, the use of fractals and other mathematical methods, as it was these that formed the real basis of the synthesised terrain software. The landform modelling and process-response modelling tended to be 'icing on the cake' and was used for 'super-realism'; these techniques are described in the appropriate chapters on landform types (i.e. Chapter 4 on rivers etc.), otherwise this 'methods' chapter would be too large.

Another point is that one could also include 'general mathematical models' in the list above to take account of fractals and so-on, but these are best covered individually. For example, interpolation and Kriging techniques were also used when necessary, following the extensive literature on this type of interpolation technique (Oliver and Webster 1990, Mason *et al* 1994). Each of these methods is examined, although it was found that a combination of techniques - sometimes as a result of phasing them in a certain order - paid off and produced the best results. This was partly based on 'intuition' and partly on 'trial and error', but mainly based on a sensible order of staging synthesised terrain through a cycle of methods until a desired result was obtained. Naturally the methods had to reflect the results required and the resources available. Some of the conclusions about the efficacy of the methods were quite contrary to expectations, and these are discussed in the appropriate chapters.

3.3 Terrain Evaluation

3.3.1 Terrain Classification - Overview

One method of generating synthesised terrain is to base the product or target DTM set on a real source. To do this, the DTM must clearly have a sound basis in real terrain data if it is to provide an adequately realistic terrain representation. To use this in a software tool, the proposed process for the generation of synthesised terrain could start with the user selecting a region of the world where he or she wishes to model, providing that a specified range of scenarios or options exist in the form of available map data (or indeed, simply maps of adequate scale). The act of selecting the geographical region of the scenario (known as 'Area of Responsibility' or AOR) will then give rise, by applied methods, to a range of defined parameters associated with that part of the world. These will in turn broadly influence terrain features and individual landforms, and may be used directly in software algorithms. These include parameters associated with:

- Geomorphology - the form of the earth's surface
- Geology
- Hydrology and the general characteristics of stream systems
- Climate - rainfall and evapotranspiration
- Vegetation characteristics.

On a human geography or 'infrastructure' level similar parameters would be:

- Population patterns
- Urbanisation and industrialisation characteristics
- Communications and their characteristics
- Infrastructure characteristics

- Land use (crops, market gardening, parks etc.)

These general topics can be represented quite satisfactorily as data sets, and they are obtainable from a range of sources (e.g. the Digital Chart of the World (DCW) database -itself based on maps such as the ONC (Operational Navigational Chart) series - see the section on web sites in chapter 2). However useful such sources are individually, they will inevitably lack the kind of descriptive terrain detail needed to act as inputs to the generation processes. This detail must in turn be derived from terrain evaluation or classification methodologies.

3.3.2 Terrain Classification Methods

As is discussed in the following paragraphs, there is a wide range of terrain evaluation or classification methodologies which have been developed by different agencies over the world. These tend to fall into two categories:

- Physiographic or landform-based methods. These are based on a hierarchy of landform types which are largely qualitative in nature and are based mainly on descriptive features (i.e. appearance and type)
- Parametric methods. These deal with more quantitative descriptive parameters and are based on measurements

3.3.3 Relevance of difference methods to this research

The research programmes that led to this PhD work are together regarded as a series of unpublished projects or working papers, created by the author, many of which produced software applications. Each application required elements of all the available methodologies - the physiographic approach to allow the user to select the type of landform on which the simulation (such as an army training exercise) could take place, and the Parametric method to provide the tangible quantitative parameters to act as inputs to the process-based generation algorithms (which would be an additional stage to provide additional 'realism' and 'geomorphological integrity'). The physiographic method was also known as the 'dial-up' method, since it allowed the user to produce an 'imaginary' version of a real area on demand, providing certain preliminary requirements were fulfilled.

It was intended that a selected and developed terrain classification methodology was to be applied generally - via the user's GUI (Graphical User Interface or customised window) in two stages. As a first step, the GUI (as a front end to Geoforma) presents the user with a range of descriptive 'landform' types which are characteristic of the specified scenario or region, and from which the user can start to make a preferred selection (see Figures 3.7 to 3.10, which show the GUI in use.) Figures 3.7 and 3.8 demonstrate that the user can 'check' the terrain to monitor progress, having gathered the various data and 'run' the synthesised terrain modules. Figure 3.9 shows a view of an AOR prior to committing it to hard copy. Figure 3.10 shows the relative change (in abstract terms) from the real 1:500,000 map to a parameterised version (portrayed as vectors and 'meta-data' - which is simply descriptive material used in the computer processing. Note that computer models need 'metamodels' in order to transpose abstract data into computer-readable formats).

As a second step, the nature of the landform type selected would permit the identification of landform-associated parameters to act as inputs to the algorithms. This provided a detailed quantitative framework for the synthetic terrain generation process. The second step in the terrain classification methodology also acts as a transfer mechanism between the qualitative landform descriptors with which the user is presented and the terrain-related parameters which

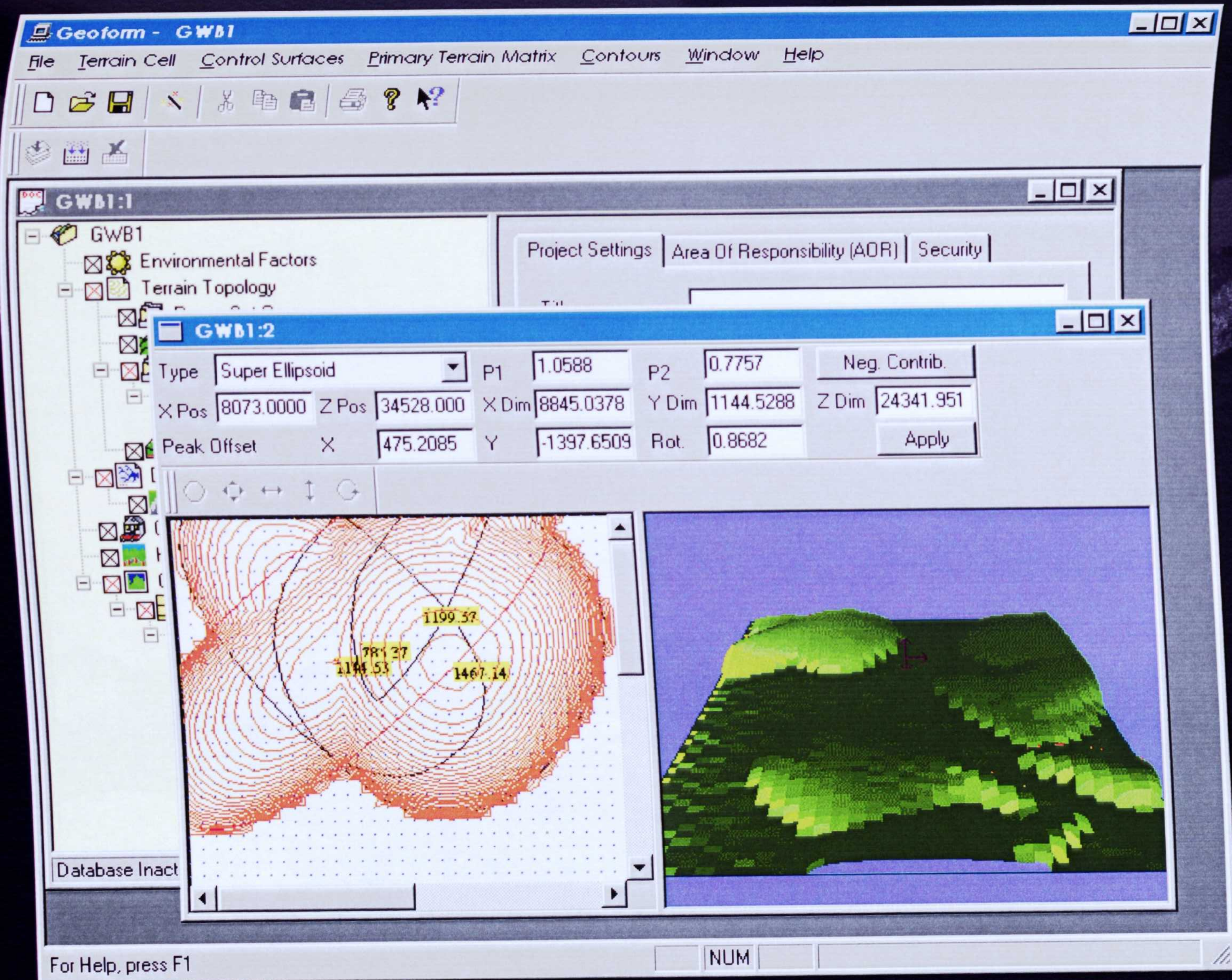


Figure. 3.7 View of the GUI for the GEOFORMA 'desktop' for a typical user

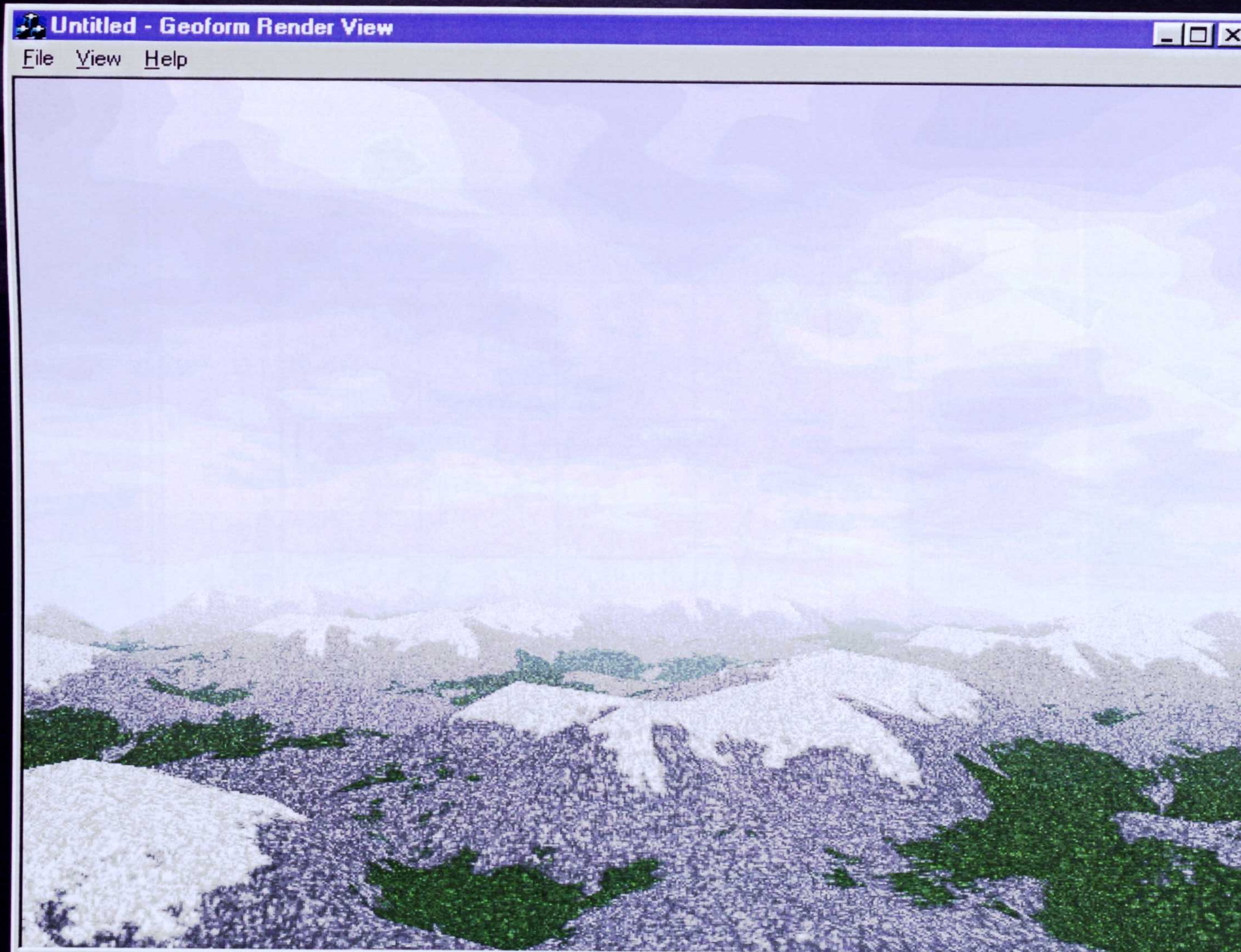


Figure 3.8 Viewing the terrain at design time in order to check progress

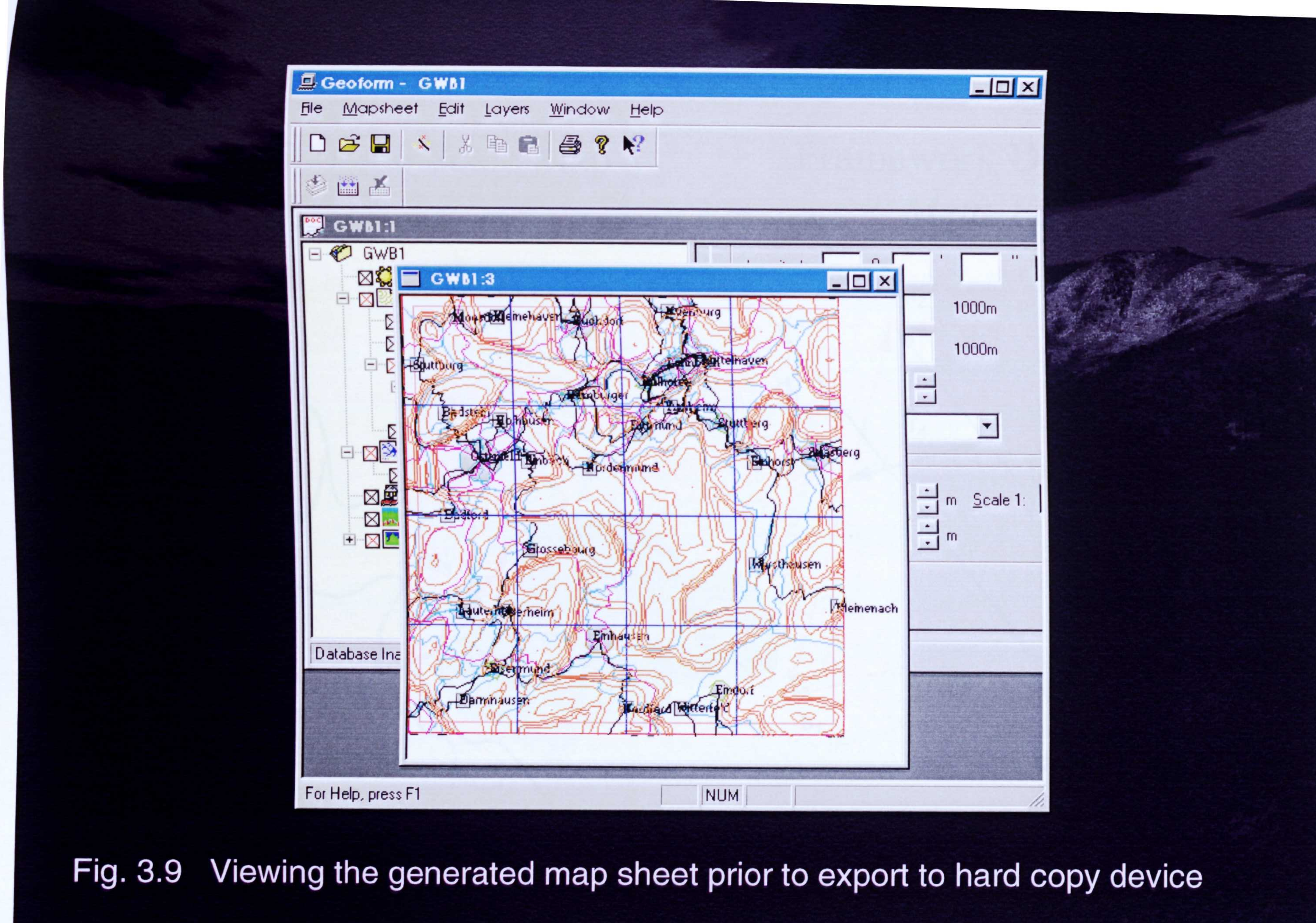


Fig. 3.9 Viewing the generated map sheet prior to export to hard copy device

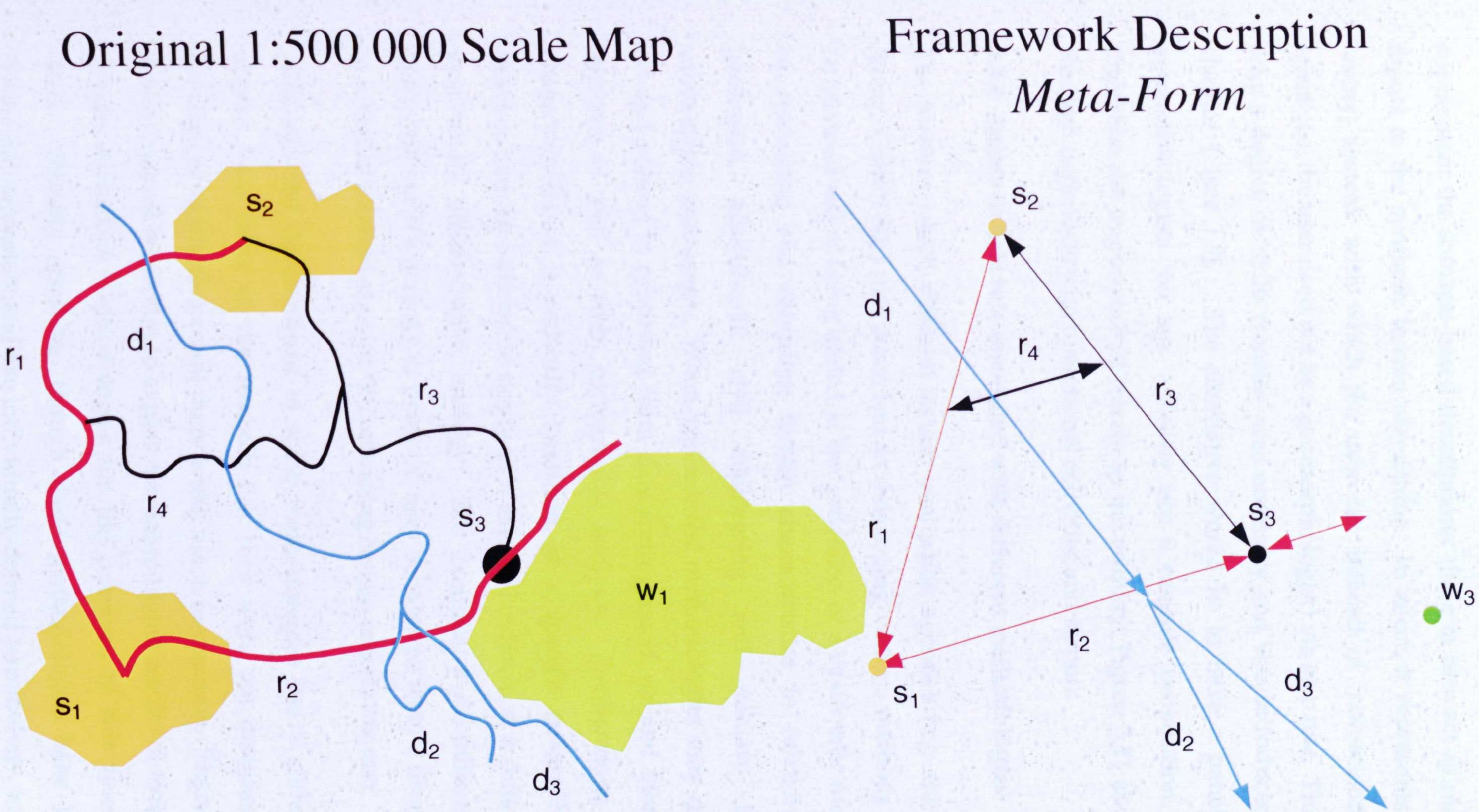


Fig. 3.10 Map Framework

supplement the scenario-based descriptions: these in turn act as major inputs to the synthetic terrain algorithms. In effect, it represents an 'expert system' with which the user can interact in 'non-scientific' terms (i.e. the user need not be a geomorphologist) via step one. This is why a degree of 'skills transfer' was necessary and was introduced in chapter 1 (see 1.9). The alternative would be to have a panel of geomorphologists 'on tap' - clearly not a realistic proposition. To underline the importance of terrain to the military, Figure 3.11 shows the high dependency on operational activities and terrain.

3.3.4 Access to data sets associated with different methodologies

The motives which different terrain evaluation agencies (e.g. the US Army, CSIRO etc.) may have had in developing various methods can be summarised at being aimed at the provision of a systematic means of evaluating and recording terrain characteristics in relation to geological, agricultural, civil engineering and military land exploitation and usage. When applied, the methodologies may draw on and present in processed form data from ground, air and satellite surveys as well as from cartographic analysis. Furthermore, the characteristics of a particular landform at a specific geographical location may be inferred to apply to a similar landform at a different location by physiographic analogy. For example, a drumlin on a glacial till surface geology at point '**X**' may be inferred from a drumlin at a similar location at point '**Y**', providing certain criteria are met.

Although the development of these methodologies has a different motive from those of the research (i.e. they were not designed to simulate or synthesis terrain) there is still much in common. Therefore it was deemed important to exploit the accumulated results of existing terrain evaluation methodologies for the purposes of this research work. Broadly speaking, though these methodologies have been developed separately and use individually-defined terminology, in this

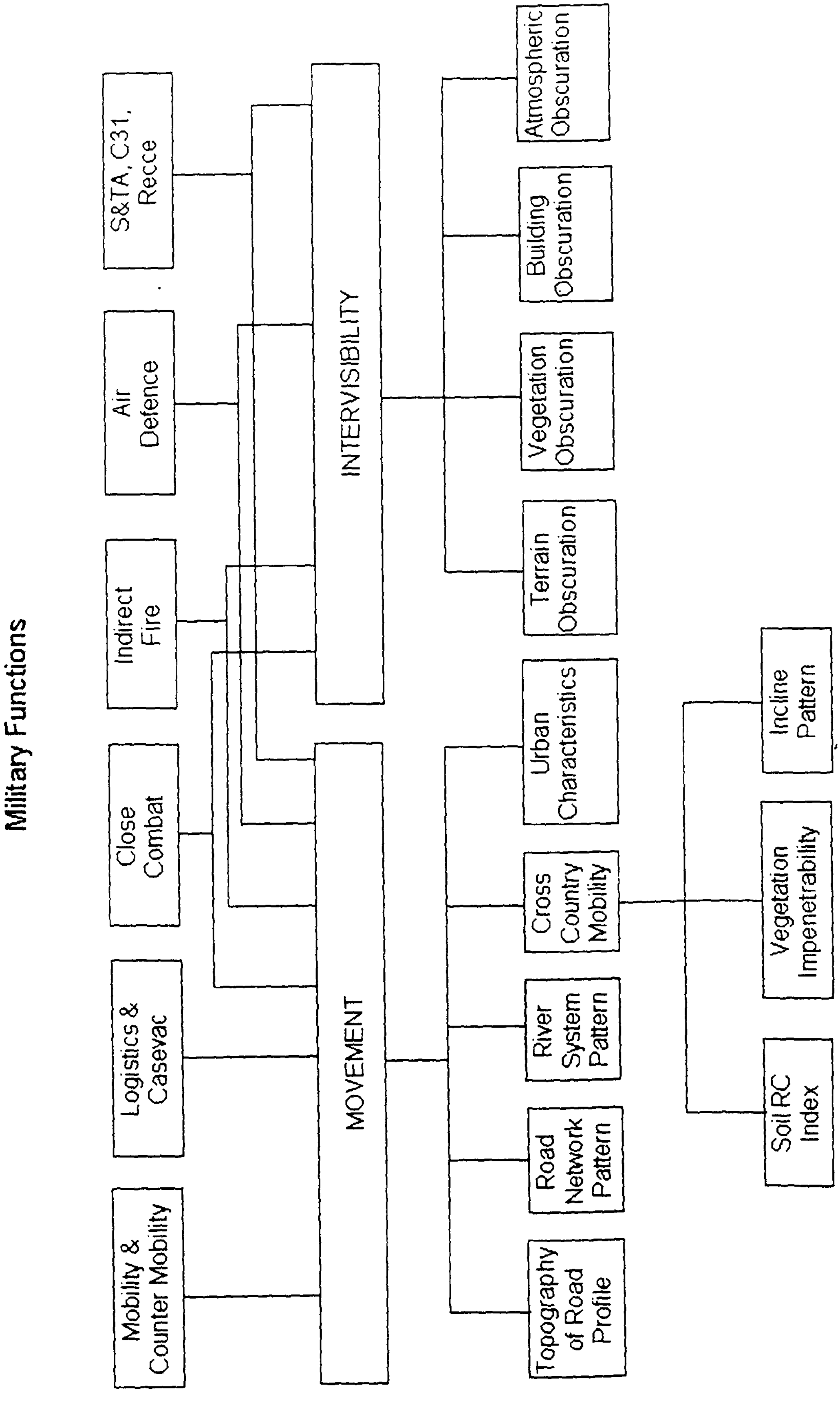


Figure 3.11 Relationship between terrain and military functions

thesis it was noticed that there is a degree of correlation between some of them, particularly where they address similar objectives. This principle opens the prospect of a kind of cross-translation of results, which has provided access to the accumulated work resulting from the combined (but differing) methodologies.

3.3.5 Objectives of the classification selection activities

The terrain classification methodology generates a selection activity which is documented in this chapter. The activities have the following objectives:

- To define the terrain characteristics which are required for the creation of synthetic DTMs, originally inspired by the need to provide army training models. Also, to recognise which representations are unnecessary or 'untenable', and thereby to avoid the allocation of effort. The interpretation is provided below.

- To define the required characteristics of the Geoforma suite of software with respect to the terrain classification system

- To review existing terrain evaluation methodologies. A brief review of these is provided below

- To select the most appropriate classification methodology and define its proposed development as far as possible. The detail is described below, along with proposed areas for development.

- To define the additional work required to provide adequate inputs to the algorithms for the first years' of research work. Various scenarios were examined and these are documented below.

In the author's research, it was considered important to identify at the outset which terrain parameters were required to represent terrain adequately for the purposes of army training. This in turn created a number of dependencies between terrain characteristics and the basic military functions which were to be used in the army simulation training software. These military functions and their corresponding terrain dependencies are shown in diagrammatic form in Figure 3.11. This diagram is interesting and relatively important in that it shows how the application of terrain to military functions is related (at least from the military point of view), but it does not impinge directly on the general principles of creating terrain synthesis algorithms. In more detail, the diagram shows that military functions (such as logistics and 'casevac' - casualty evacuation) are related to either movement and/or intervisibility. This in turn can be traced down the diagram (which is an organisational or dependency chart) to specific requirements, such as 'terrain obscuration' or the need for a 'road network pattern'. In this way the user can 'create' terrain most appropriate for his particular need. Examples would be perhaps the simulation of undulating terrain with wooded areas for an anti-tank gunner wanting to track the path of a simulated target moving behind features, or a flat area devoid of vegetation or relief features for helicopter simulations concerned with casevac (casualty evacuation) or logistic operations.

3.4 Background discussion

From the considerations outlined in the previous paragraphs, it may be inferred that for the purposes of military (mostly army) training a number of terrain characteristics must be represented. Further work showed that these characteristics were in fact general items which were germane to any application, whether it involved army training or not. Briefly, the characteristics are as follows:

- The terrain surface topography (i.e. the 'bare relief')
- The drainage system/stream network

- Areas of standing water
- Coastline
- Soil trafficability ('going' or mobility for Armoured Fighting Vehicles (AFVs) and other vehicles - emergency service and rescue as well as military)
- Vegetation (and its effect on obscuration)
- Urbanisation settlement patterns
- Road and other communication networks
- Rural settlement patterns
- Infrastructure features (docks, railway sidings etc.)

The algorithms which were designed to create these features, and thereby would create synthesised terrain, were found to be largely process-based, where 'process' might vary from the effects of erosion on a terrain profile (slope) or the effect of topography and geology on the patterns of the drainage systems. The effect of urban and rural settlement was also considered but this was not researched at the same level of detail as physical terrain; this thesis deals primarily with physical landscapes.

However, it was found to be difficult - in some cases virtually unthinkable - that such physical processes could be generated from first principles without reference to real data. It was said by one of the senior army officers sponsoring the programme of work that *'terrain is difficult to create with only a blank sheet of paper'*. What he meant is that the algorithms were satisfactory in their own way, but they had to be primed, conditioned and bounded by the primary parametric descriptors drawn from the real world - which in turn would be provided via a terrain classification system. The better the input data is 'rooted' or defined in terms of reality then the better the chances are of not misrepresenting realistic terrain and of obtaining a good end-product.

This in turn leaves open the philosophical question: *if you take real terrain as a template, are you really synthesising terrain at all, or just 'twisting' it to form a sort of mirror image?* It must be said that this issue is examined in detail later in this thesis, but for the pragmatic purposes of creating cheap and rapid 'realistic' terrain, the question was brushed aside as irrelevant. Accordingly, the process-based algorithms were invoked to provide detailed infill to the coarse structure which was parametrically and statistically defined by reference to real data. This data is in turn associated with the landforms which are to be represented. The general requirements for the classification system and the requirements in relation to each terrain characteristic are discussed in the following paragraphs.

3.5 General requirements

At this stage in the research, before any software was written, the requirements of the classification system were reiterated and summarised as follows:

- The system should be based on real data from terrain evaluation work and from cultural and climatic data derived directly from reference to the known scenario area.
- Selection of required terrain types must be by reference to qualitative descriptive landform types which are meaningful to whatever user is operating the eventual software system (e.g. military user, civil engineer, etc.).

- Having selected a landform type the classification system must operate as an 'expert system' in the broad sense of the term, and be capable of producing parametric terrain descriptors which characterise the coarse nature of the terrain to be synthesised and which will act as inputs to the terrain synthesising algorithms.

3.5.1 Requirements for a parametric classification of terrain surface or 'physical topography'

Accepting for the moment that the emerging system had to be simplified to allow software engineers and Army personnel to understand it, the work continued with the establishment of some basic requirements. These were later mapped against existing, documented landscape evaluation or classification systems and the requirements were refined. However, the early work had to start with some basic 'rules of engagement', which are described as follows.

The terrain surface (the physical landscape or topography - without 'culture' or vegetation) was defined, in essence, as a two-dimensional surface with a pattern of undulations which make up the third dimension of elevation, and which could be considered to be characteristic of a particular landscape type. The nature of these 'undulations' (which could include landforms) depended on the scale of terrain unit being considered. For the purposes of 1:500,000 representations, for example, only 'coarse' features were represented. Broad descriptors of these features were needed to act as a framework for the terrain algorithm which was designed to utilise geomorphological theory to produce a terrain surface which would be consistent with the framework parameters and with other factors (e.g. geology) which helped characterise the scenario location or 'region'.

As a minimum requirement, the following parameters were needed to characterise the terrain surface:

- **General Qualitative Descriptors**. These included 'Physiography' (e.g. meaningful descriptors like 'plateau' or 'plain') and Hypsometry (e.g. general altitude and 'landform' expressed as known geomorphological landform types). These were intended to guide the geomorphological aspects of the terrain algorithm.

- **Plan Geometry form parameters**. So-called 'uplift features' (hills, escarpments etc.) can have characteristics such as parallelism and randomness in different degrees and these features may have quite different degrees of linearity. Parameters are needed to quantify these characteristics.

- **Profile form parameters**. Uplift features may be peaked or flat-topped; a parameter or index is required to quantify this characteristic

- **Profile wavelength parameters.** The mean inter-crest distances together with their variance characterise the plan scale of surface undulations

- **Profile amplitude parameters**. The mean crest-to-valley distance together with its variance characterises the vertical scale of surface undulations.

Other important requirements identified were as follows:

(a) **River system characteristics**, including:

- Density of river channels in network (= part of the drainage basin)

- General drainage direction (= direction or trend of flow)

- Distribution of stream channel widths

- Distribution of river flow rates

- Nature and condition of river margins and banks.

The importance of rivers to military training is obvious, successful advance or retreat may depend on the type and size of rivers, and the importance of bridges cannot be overrated. One only has to think of Napoleon's desperate, retreating army moving across the River Beresina in 1812 (Clery 1880) or the debacle at Arnhem in 1944 (Johnstone 1977) to understand the fixation army planners have with bridges (see Featherstone 1998 for a full bibliography).

(b) Soil characteristics

Trafficability (movement of heavy vehicles) - sometimes referred to as mobility - depends on the type of soil, the water table and the prevailing conditions. This in turn affects the RCI (Rating Cone Index) of the soil. Correlation between the RCI, the geology and soil, the water table and the soil type should be matched against the terrain surface. It should be pointed out that UK Geological Survey (now the British Geological Survey) maps differentiate between solid geology and surface deposits (or drift). Where appropriate, the distinction is made in this thesis.

(c) Vegetation Cover patterns

Vegetation is only important as a requirement to the model at this stage in that it affects intervisibility and trafficability. The parameters for vegetation might include:

- Vegetation (e.g. tree) height and type (e.g. deciduous woodlands are barer in winter)
- Forest or woodland canopy density
- Location tendencies (e.g. in North Germany trees tend to be grown as small stands on hilltops)

- Vegetation trafficability retardation factor

- Other factors such as seasonal effects, reflectivity indices, hue, colour etc. which could be useful inputs to a GIS analysis or display system.

(d) Urban Area patterns

Urban areas provide complex and difficult fighting environments (remembering that these parameters and requirements are driven by army considerations. The recent work on the battle of Stalingrad by Beevor (1999) demonstrates this problem admirably. Some factors include:

- Mean and variance of areal occupancy of cities

- Mean and variance of areal occupancy of towns

- Terrain location correlation (e.g. by rivers etc.)

- Mean and variance of inter-city and inter-town distances

(e) Road network patterns

These can be described by the following:

- Mean and variance of inter-nodal distance

- Distribution of road capacities (to carry classes of vehicles)

- Mean and variance of inter-bridge distances (see Featherstone 1998 for the importance of bridge attributes in a military context)

- Occurrence and frequency of defiles

- The tendency of roads to complete an 'S' bend before negotiating a river or railway, especially if intersecting the line at an acute angle (see Figure 3.12). The diagram shows that a road meeting a railway, other road (i.e. at a different level) or canal where an acute angle is involved tends to carry out an 'S' bend, as in example a in the figure (road 2), as the example of b - where road 1 would necessitate a long, difficult and expensive tunnel or bridge engineering. The bridge at road 1 would be about three times longer than at road 2 - it is clearly easier to cause the road to bend than create a longer tunnel or bridge. Examples are to be found on almost every OS map in the UK, although they usually involve old or well-established roads (by personal observation alone, the phenomenon appears to be less common in some countries where road and railway systems are relatively new).

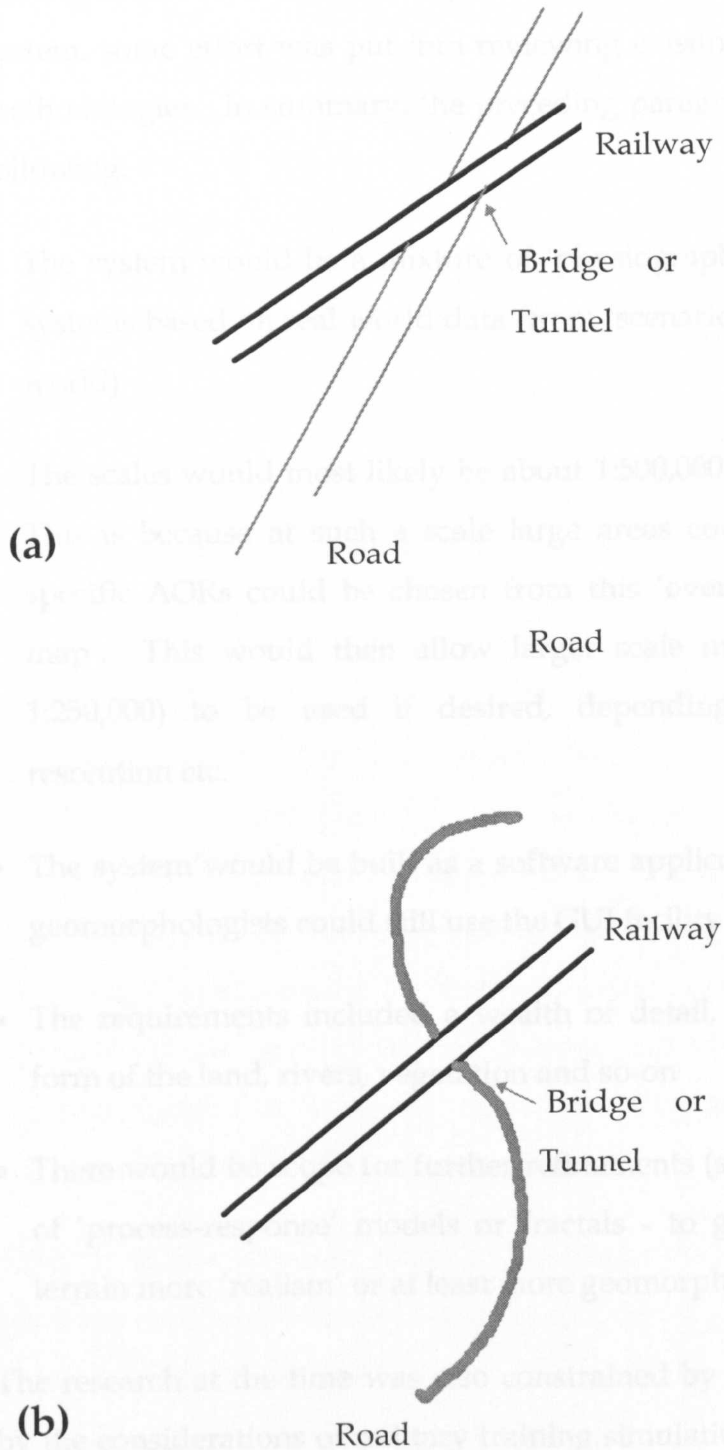


Figure 3.12 S bends and the 'acute-angle' approach algorithm

3.6 Review of Methodologies

Having established the basic requirements and points in the intended system, some effort was put into reviewing existing and documented methodologies. In summary, the preceding paragraphs suggested the following:

- The system would be a mixture of 'physiographic' and parametric systems based on real world data (from 'scenarios' or regions of the world)

- The scales would most likely be about 1:500,000 as a starting point. This is because at such a scale large areas could be viewed and specific AORs could be chosen from this 'overview' or 'reference map'. This would then allow larger scale maps (1:100,000 and 1:250,000) to be used if desired, depending on the required resolution etc.

- The system would be built as a software application on which non-geomorphologists could still use the GUI facility

- The requirements included a wealth of detail, including the basic form of the land, rivers, vegetation and so-on

- There would be scope for further refinements (such as the inclusion of 'process-response' models or fractals - to give the synthesised terrain more 'realism' or at least more geomorphological integrity).

The research at the time was also constrained by army resources and by the considerations of military training simulation. The following is an example from a working paper based on the author's text explaining the need for the approach:

> *"It has long been recognised that knowledge of the characteristics of terrain for various activities (engineering, military, land*

management et.) needed to be co-ordinated to share experience and avoid costly mistakes. This is especially vital when the planner is confronted with unknown terrain and the appropriate knowledge needs to be accumulated fast and efficiently.

To facilitate this need for information a system is required that can learn from the experienced and aid the decision-making of the planner. A system which can classify terrain into generic units and provide knowledge from previous analogous terrain types would be a great advantage in this respect"

The author goes on to introduce the two methods, the parametric method, which was paraphrased by a colleague by request;

". . . this involves the mapping and measurement of the factors which are considered to be critical given the envisaged use of the land. A superposition of the resulting maps will give a complete classification, and this is known as the parametric method. Alternatively, a method whereby natural terrain features and underlying geology are recognised and classified at different levels of magnitude according to the terrain under consideration . . is known at the 'generic' method at large map scales and as the 'physiographic' or 'landscape' method at small map scales" (RED Scientific Working Paper No 1, 1994).

Apart from the common mistake about map scales (where large-scale maps are confused with small-scale maps) this is a good understanding of the methods to be used as defined by the author. These methods are enlarged and described in more detail below:

3.7 Parametric Methods

A parametric method is defined (Mitchell 1991) as the subdivision of land on the basis of selected attribute values. The data collated from sample points for each factor can then be handled numerically by computer for further analysis. This method of terrain classification has been used extensively in North America by the Canadian Army, the US Department of the Interior and the US Army Engineer Waterways Experiment Station (USAEWES), among others. Indeed it was the USAEWES that developed the so-called 'Vicksburg' method that is used in the research programme described in this thesis. It was found that although the Vicksburg method is good at characterising the shape of the terrain (mainly for army mobility studies), it lacks the scaling parameters which are felt to be essential for synthesised terrain generation. Therefore some refinements (mainly scaling) have been drawn from the Quartermaster Research and Engineering Centre, Massachusetts, known also as the 'Natick' method (US Army 1960). Indeed, the final approach towards building the algorithm in this thesis was the Vicksburg method refined by elements of the 'Natick' system, simply because this was relatively easy to turn into an algorithm. Naturally, the work of some of the other workers mentioned (Speight (1973, 1974) and Mitchell (1991)) were also used as a basic reference set which, if any issues arose, could be consulted.

The techniques described below are common to all of these agencies. The classification method starts by choosing those factors which are judged important for the task for which the land is to be used. For example, for flooding a valley because of a hydro-electric power dam project, the value of the land and the volume and size of the projected dam can be taken into consideration. It might, for example, be better to build two or three dams rather than one large one, with a consequently lesser impact on the land in the stream valley. The land is then generally surveyed by means of ground surveys, satellite or aerial surveys or some other appropriate method of collecting data. The factors are then derived directly or indirectly from these sources.

The terrain can either be randomly sampled for the values which underpin the factors, or the sampling can take place using a grid system with an interval (which determines the resolution or coarseness of data) according to the level of detail required. The factors are then loaded into a database and correlated and analysed accordingly. This is done with a GIS to present the data visually at the level of detail required. Once this has been completed it is possible for the agency involved to determine which areas of the landscape in question are appropriate to the proposed land usage and which are not suitable or appropriate. There can be varying levels of 'suitability' in between. Terrain attributes in a parametric map must be recognisable and measurable in the field and must be defined at scales appropriate to the land use under consideration. When parametric classifications are used for terrain, certain inherent problems must be considered. The most important of these involves the choice of attributes to be mapped, as well as their subdivision into classes (and a class hierarchy). In theory the classes would have to be recognisable on the ground, since recognition in the field is a way of validating the classes, thereby adding credibility to the overall method.

It should be noticed that this method is similar - indeed nearly identical - to collecting real data for DTMs, although the process can be simplified if only certain factors (like land use) are required. This process would therefore involve a cost, so using parametric methods to support synthetic terrain *per se* does not make sense in economic terms - it is only useful to the synthesised terrain modeller when such exercises have already been carried out and terrain classification data is therefore already available.

3.8 Landscape Systems

It is generally argued that every country may be divided into a finite number of physical regions, each with a characteristic landscape

(Beckett 1976). Indeed, geography text books in schools still attempt to divide the island mass of Great Britain into regions such as 'the Weald', 'East Anglia and flat/fen country', 'the Welsh Marches' and so-on. Although somewhat subjective, this is psychologically a system of 'geographic anatomy' with which it is easy to relate. Schoolchildren in London can visualise Wales more easily if they are shown slides of the Brecon Beacons and Snowdon, even if the area has probably only about 10% of its land above 150m OD (this is an estimate). There is, therefore, perhaps a subjective - even emotive - element in these classifications - but this does not necessarily disqualify this from being a useful terrain synthesis preparation tool.

Therefore, it appears reasonable that landscape systems can be used to divide terrain into areas according to their degree of similarity. At one end of the scale the world can be divided into 'land zones' representing - in a very general sense - major climatic regions. Each zone can then theoretically be divided into 'land divisions' and then further into 'land provinces' and so on down to 'land facets'.

The information below is derived from a group of sources, notably:

- The Australian CSIRO 'institute' (Christian and Stewart 1968)
- The UK Oxford-MEXE-Cambridge groups (Beckett and Webster 1969)
- The South African National Institute of Road Research (Brink *et al* 1968)
- The University of Melbourne (see also Mitchell 1991).
- Works such as Leigh (1974) and Mitchell (1991)

These bodies developed terminology to describe landscape systems, and about seven levels of terrain units at different scales can readily be equated with actual ground information. An important aim of this system is to be able to infer characteristics about an unknown land facet using a similar known land facet, based on the theory that there are only a finite number of facets which comprise the earth's surface.

The Division of Applied Geomechanics (within the CSIRO in Australia) required an engineering assessment application of the landscape application system outlined above and was therefore compelled to devise a modified system. This system was characterised by more narrowly-defined land systems and land facets, which were proved by engineering experiment and defined entirely in terms of recognisable features before specific engineering data sets were attached to them.

The terrain evaluation process was visualised (Aitchinson and Grant 1968) as comprising three phases:

- The establishment phase
- The quantification phase
- The interpretation phase

For example, the establishment phase consisted of terrain classification and mapping which was rigorously aimed at engineering requirements. This brought classifiers and users together so that the latter could, without training in any of the earth sciences, not only operate the system but also build their own requirements into the original classification. The land classification was based entirely on land properties normally recognisable by engineers and avoided abstraction at all levels. There were four levels of generalisation (in descending order of size):

- Province

- Terrain Pattern
- Terrain Unit
- Terrain Component

Only the last three were considered as suitable storage units for engineering data. The method of relating such data to these was called the PUCE (Pattern Unit Component Evaluation) programme - see Mitchell (1991) for details. The PUCE programme, although some 20+ years old, still provides an ideal method with which to progress any specialist land classification evaluation project, as it allows the users to mould it to their own purposes.

3.9 Land Classification and its application to synthetic terrain

The aim of this part of the study was to be able to generate a synthetic, yet apparently realistic, terrain, which would be based upon a pre-selected region or area. This is the so-called 'dial-up a landscape' method. Although this was perhaps a rather shallow name, it stuck in the minds of the MOD users. Clearly, in an ideal sense, the landscape system should allow an area or region to be divided into these building blocks, ascertain the proportion of each 'block' for the region and then recreate a totally synthetic yet statistically valid terrain, which is representative of the original area/region.

To recreate the appropriate land facets (called 'building blocks' by the non-geomorphologists on the project) using a computer-based algorithm, would require information about each distinct type of facet encountered within the area/region selected.

Not every detail about each facet was required as some were thought to play no or little part in the military operations at which the terrain synthesis research was originally aimed. For example, soil fertility was not regarded as a prime military based detail, although it does have intrinsic value. It was suggested that a database could hold every facet and every detail, and an index system could be used to differentiate which details would be useful for a particular user. The point of the facets, as mentioned, is that new facets can be created using the 'template' information on each distinct ***measured*** facet. This is clearly one of the main advantages and perceived benefits of using the parametric system of land classification to underpin terrain synthesis operations.

Statistics would also need to be gathered on the average dimensions and variance of each facet, what facets border each other facet and with what probability, and how likely each facet is to appear in the given area or region. For example, drumlins are likely to occur in 'fields' of multiple landforms (facets) in areas that have been glaciated; the probability of drumlins occurring next to tropical facets is very low (although the possibility of encountering relic landforms should never be discounted). It is this refinement to the landscape classification programme that made the knowledge of earth scientists - particularly geomorphologists - so important).

The statistical approach might also be relatively simple for a 'pre-landscaped' area, but will mean that a portion of 'virgin' country will need to be landscaped in order to determine these statistics. In other words one does not get something for nothing, and unsurveyed terrain needs to be surveyed, at least to some extent.

The size of the area to be landscaped was found to vary according to the diversity of the area/region which the user wanted to be modelled as part of the terrain synthesis programme. Also, the diversity of landforms was an important factor - featureless plains were easier than pro-glacial limestone areas richly endowed with numerous 'classic' landforms. This is not to overlook 'process-oriented' approaches -

these could be superimposed to provide exquisite detail - such as the intricacies of a stream network. Indeed, the author was forced to change the hypothesis put forward in the start of the work that 'process-response models' would show the way; quite the reverse was found to be true, as process-response models are difficult to build on a 'blank sheet of paper' and need a real region in which to be based. This does not undermine their validity - it merely places them as a secondary or tertiary stage in the search for synthesised terrain realism and integrity. This argument is revisited in the conclusion chapter.

3.10 Summary of terrain classification methods reviewed

Using a mixture of both parametric and landscape methods of classification, it was possible to model and generate synthetic terrain via the specially constructed program suite Geoforma. Admittedly this is not a fully-automatic process; much work had to go into the creation of facets for real world regions or areas.

Full use of the PUCE programme of work was found to be unsuitable because it required such a complete classification of the AOR under consideration. This in turn was found to require extensive effort and time unless some shortcut method could be found. It also helps, of course, that an area has already been mapped and subdivided into whatever physical regions the particular method uses. Germany was found to be a suitable starting point for several reasons:

- US (NATO) DTED and DFAD terrain data is already available at a high resolution (i.e. 100m horizontal gridded interval).
- The country has been broken down, by military engineers, into physiographic regions.
- The research sponsors were still fighting the 'cold war' at the time the research began so Germany was still an obvious flashpoint

between NATO and the now defunct Warsaw Pact forces. This meant that there was much collateral material in terms of data, articles, exercises, etc.

- The author visited Germany and took many photographs while on a visit to study intervisibility with the then British Army of the Rhine (BAOR) in the mid 1980s.

- The MOD sponsors were familiar with Germany and Northern Europe and had lived there for long periods.

3.11 Selected Method

From a survey of the various methods available, the USAEWES 'Vicksburg' method was found to be the most tractable and efficient way forward, combined as it was with elements of the so-called 'Natick' method.

The quantification of the parametric factors for the AORs was largely possible by map analysis using a computer-aided GIS map analysis approach. The landform aspects should enable cross-correlation with other methods to unlock data sources already evaluated. This was the so-called 'dial-up' function: *it comprised extrapolating results for classified terrain to other locations by the means of physiographic analogy.*

3.11.1 The chosen classification system

The chosen classification system differs fundamentally from other classification systems in that it was changed to provide parametric inputs to a synthesised terrain model. In a nutshell; this system helps create synthesised terrain DTMs, whereas the others merely describe terrain of similar type. The basic Vicksburg methods was therefore adapted and extended to provide this additional required functionality. In addition, map studies were carried out as part of the algorithm definition exercises in order to quantify terrain parameters for the scenario areas under consideration. In other words - there was cross-checking with small-scale maps to check that the system worked, and inevitably some manual work was required.

The method was aimed therefore at evaluating the effects of terrain on military activities. It is based on defining a range of terrain characteristic factors but limited to a manageable number. These factors are easy to visualise, simple to map and were important to the military mind (although they were also thought to be fairly generic - there is nothing about terrain that is inherently 'military' - it is the interpretation of that terrain that gives it its military attributes with features such as defiles, dead ground and intervisible points, bottlenecks, killing grounds, reverse slopes and other terms. Some of these terms have no real counterpart in the earth sciences - and are purely military adaptations of terrain. The Duke of Wellington, for example, had a favourite tactic of deploying his army out of sight and harm on the reverse side of a slight ridge until their moment came for action; in this way terrain contributed to the battle of Waterloo (Brett-James 1972, Chandler 1996) and in the Peninsula War battles (Glover 1996) the position of river crossings, escarpments and reverse slope was crucial to Wellington's tactics. Importantly, the Vicksburg method is thought to 'rise above' military descriptors - even though it is generated by military agencies - and provide a complete picture of terrain.

The method's strength is in its combination of qualitative and quantitative sets of parameters. Both are useful in the later stages (e.g. in the 'process-response' refinement stage model, should one be applied) and the qualitative descriptors provide projection to other areas by physiographic analogy. These are examined briefly:

3.11.2 Qualitative Parameters

The Qualitative Parameters comprise Physiographic, Hypsometric and landform/surface descriptors, where the first two have already been described, and the third descriptor includes qualitative descriptor families of surface geometry and form, ground and vegetation.

Geomorphological descriptors can be added - these include more precise or specialist technical terms (karstic features such as dolines, limestone pavements and gorges, volcanic and intrusive features, periglacial features, outwash features such as eskers etc., and rock features such as tors, inselbergs, buttes etc.).

3.11.3 Quantitative Parameters

Quantitative Parameters include a characterisation of the following:

- **Slopes** - This is a classification of slopes (tangent of incline) in the area evaluated. The classification system observed 'natural' tendencies for slopes to cluster at values of: 0.05, 0.1, 0.2, 0.4 and 0.8 as these conformed - apparently - to the relief characteristics of the area. The clustering is difficult to explain without intense geomorphological investigation into the complex relationships between geology, climate, runoff and many other factors, and while this is interesting and required documenting, it was not necessary for the purposes of the synthesised terrain work.

- **Relief** - This is the maximum difference in elevation per unit area Feature plan shape - 'Uplift features' (a general term used not to describe physical or tectonic uplift but 'positive' relief - hills and knolls) can show different degrees of linearity and feature positioning may range from apparently parallel to apparently random. These attributes are characterised by the elongation number which defines linearity, and the parallelism number. Some examples of plan shapes are shown in Figure 3.13, which shows the Vicksburg system for terrain shape classification (after the US Army and Mitchell (1991)).

- **Elongation numbers** are defined in relation to a 'terrain unit'. This is the polygon circumscribed by the points (or vertices) at which nine randomly drawn lines from a point central to the terrain unit first reach valley bottoms. The elongation number (E) is calculated by taking the (compass) orientation of the nearest contour line to each of a minimum of eight randomly chosen points and applying the simple formula:

$$\mathbf{E = F_h\ N/Nc}$$

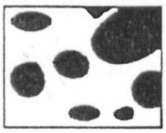
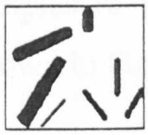
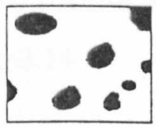
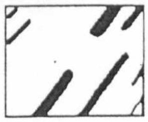
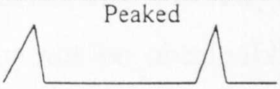
where: **N** is the number of sample points

Nc is the number of direction classes

$\mathbf{F_h}$ is the number of samples in the largest class

- **Parallelism number**. The procedure for calculating the Parallelism number (P) is an extension to the approach described in the previous paragraphs. An adequate number of terrain units are constructed by the same method and the compass directions of the long axis of each are determined by inspection. These directions are then used in the same formula as the elongation number (E). If P is between 0.31 and 0.49 the landscape is classified as having strongly parallel features. If P is less than 0.31 then it is moderately parallel, while P values from 0.49 to 1.0 suggest a random spread and no parallelism.

- **Profile shape**. Terrain features - leaving aside geomorphological descriptions and expertise for the moment - can vary from flat-topped to 'sharp' (by which is inferred a crest line or even a cuesta). This attribute is denoted by the Profile Shape Factor (S). In addition,

	PROFILE SHAPE	PLAN SHAPE			
		Non-linear Random	Linear Random	Non-linear Parallel	Linear Parallel
Occupancy	Profile Shape				
Greater than 60% of area	Flat Topped 	1	1L	1//	1L//
40% - 60% of area	Flat Topped 	2	2L	2//	2L//
less than 40% of area	Flat Topped 	3	3L	3//	3L//
Greater than 60% of area	Peaked 	4	4L	4//	4L//
40% - 60% of area	Peaked 	5	5L	5//	5L//
Less than 40% of area	Peaked 	6	6L	6//	6L//
No obvious higher or lower		7			

KEY:-

L = Linear features
// = Parallel features

Figure 3.13 Vicksburg System for terrain shape classification

the percentage of area occupied by peaks is characterised by the peak occupancy index (I_p). Figure 3.13 also illustrates the characteristics of peakedness and occupancy. If S is less than 0.5 the characteristic profile is peaked. If S is greater than 0.5, the profile tends towards flat tops. Some examples of plan/profile shapes based on the Vicksburg method are shown in Figure 3.14.

- **Profile Shape and Peakedness index.** The shape factor and peakedness index are given by the derivation:

$$S = 0.05 + 0.25(d_{10} + d_{90}) / d - 0.4 d_{50} / d$$

$$Ip = 0.1d/d_{90}$$

- **River/streams patterns.** The density of river channels in a river network and the distribution of river widths may be obtained from existing data sets of from map sampling. Flow rates (where traditionally discharge is represented by Q) and bank conditions may not be obtainable from map inspection and may have to be obtained from other sources, if possible. The whole question of river patterns is considered in a more 'geomorphological' light under the guise of process-response models. It should be pointed out that the techniques underpinning the representation of river patterns for this method are deliberately simplified and does not take account of the decades of work by geomorphologists and hydrologists. This will be discussed in later chapters.

- **Vegetation patterns.** The areas covered by major crop plantations - including forests - is a parameter readily amenable to GIS map analysis. Even a rapid manual approximation may be possible if a GIS system is not available, although this is not recommended. Data can include distribution and size/variance of forests and crops, as well as correlation with incline, soils, geology etc.

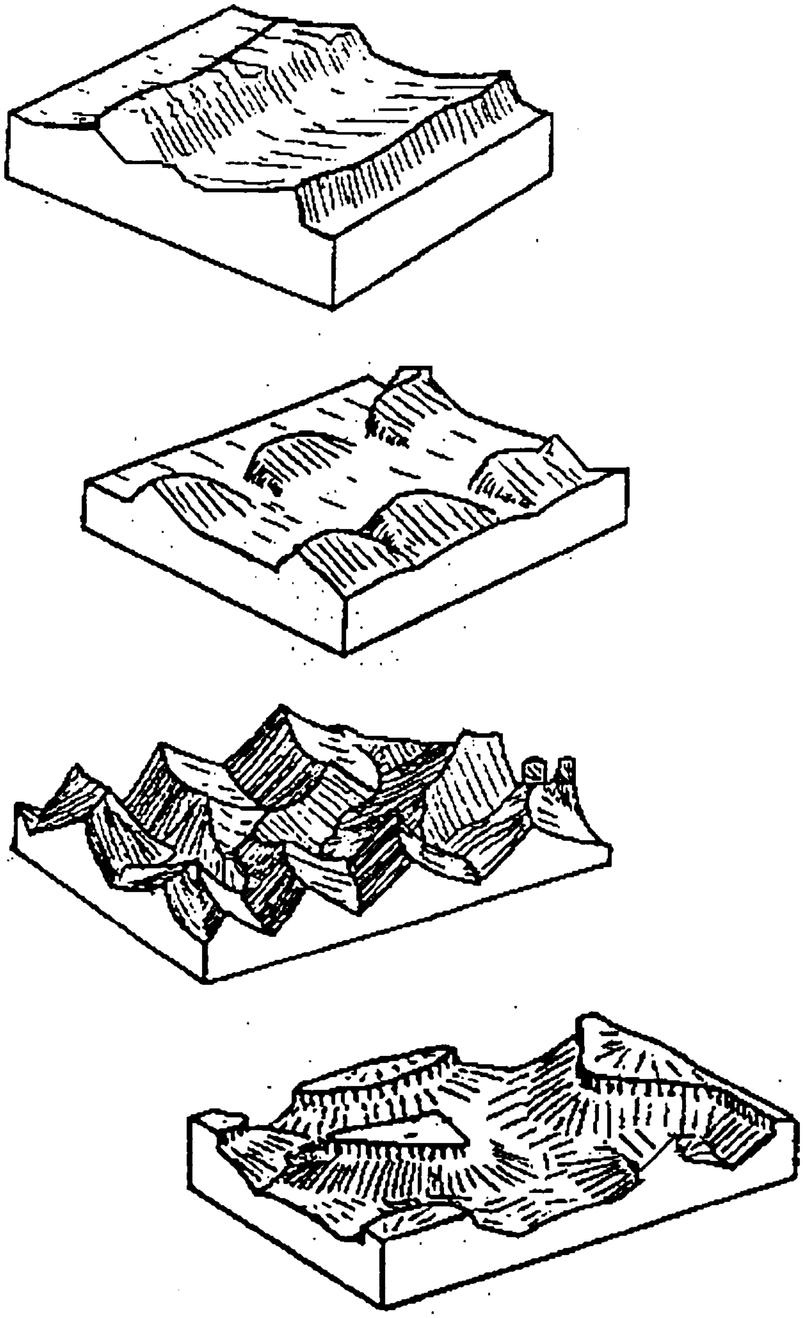


Figure 3.14 Example of plan/profile shapes based on Vicksburg Method (Based on sources: US Army EWES, Mitchell 1991)

- **'Human Geography' features** such as road patterns, urbanisation pattern and so-on. Road network parameters can yield map statistics by inspection, including mean values and variances for internodal distances, road capacities and inter-bridge distances. Urban areas can produce statistics - again by inspection - relating to area coverage and distribution. Any correlation with other features (like vegetation or slope) can be noted. Without wishing to invoke determinism, there is often a relationship between urbanisation and - for example - suitable, well-drained flat ground alongside roads and railways in valley bottoms, particularly at good fording or bridging points.

3.11.4 Data Extraction

Although there is an expectation that data from other terrain evaluation methods could be made available by cross-correlation with the adopted approach, it was only to be expected that there were difficulties in obtaining data sets in the required form. It was fortuitous, therefore, that the research programme was essentially self-reliant, and recourse to outside agencies was not required even though it may have been advantageous. Much of this problem stems from the fact that few agencies are even aware of terrain classification, and even fewer are in a position to share data sets. For this reason the so-called Vicksburg method lent itself to map analysis both in terms of manual inspection and by GIS analysis, and was therefore a good choice even if its parameters tended to be somewhat 'non-geomorphological'.

Finally, the method chosen provides the basic regional topography (and some human geography or culture features if required) on which more sophisticated methods could be overlapped, if desired. In other words the method was an option - synthesised terrain can be created without it - but it gave the modeller the invaluable asset of real data templates from real world regions for the 'dial up terrain' concept.

Moreover, the method provided a means by which the resulting terrain could be compared with the real terrain from the real world AOR or region, and inferences could be made about 'accuracy' and 'fidelity'. These concepts are examined in the chapter entitled 'validation'.

3.12 Mathematical methods - Overview

Mathematical methods involve combinations of equations which, singly or in sequence, yield the derivation for a 3-dimensional surface. This technique is well known, and has been used to describe real forms as well as relatively complex synthesised surfaces. The disadvantage of using such mathematical methods is that it is difficult to 'solve' or develop the equations that would satisfactorily describe terrain, either on a 'one-off' basis or as a generic description. Polygenetic terrain models would also be somewhat difficult to grasp. A flood plain with multiple river bluffs, for example, could be simulated, but it would be difficult to produce a model that would satisfy the parameters of all floodplains, at all scales. Even if such a vast undertaking was attempted, one might hypothesise that the worker would end up with thousands of likely models. The work involved would hardly justify the vaunted cost-effectiveness and simplicity of synthesised terrain over real terrain, and only looks at one example of the hundreds of geomorphological composite or polygenetic forms in different areas (uplands, coastlines, volcanoes, glaciated landscapes, deserts etc.) one is likely to encounter in the real world.

3.13 Fractals: Introduction and methods used

It has been suggested by Mandelbrot (1975, 1977 and 1982) and Peitgen and Saupe (1988) amongst others that realistic representations for terrain and other natural objects can be obtained using affine fractal methods. This has been explored more recently by Scholz and Mandelbrot (1989), Lam and De Cola (1993) and Barton and La Pointe

(1995). Similarly, Klinkenberg reviewed the methods used to determine the fractal dimension of certain linear features (Klinkenberg 1994), while Evans and McClean (1995) and Gao and Xia (1996) have tried to apply fractal geometry to studies of land surfaces. Still more recent work McClean and Evans (2000) has concluded that it is not clear that fractal geometry can fully explain land surfaces; and therefore it is likely that land surfaces are not 'self-affine'.

It is reasonable to state that Mandelbrot, although probably correctly identifying the existence of fractal structures in nature, can hardly have claimed to have 'solved' the mysteries of geomorphological form and process through fractals alone, and some geomorphologists such as McClean and Evans (2000) have pointed out that fractals, although important, are not the panacea for all earth science questions that was perhaps once suggested - visual similarities are not sufficient.

For example, a fractal dimension for a surface of around D = 2 could yield a picture of 'smooth rolling hills' (mathematically speaking with altitude variance concentrated at long wavelengths), whereas D = 3 would represent a surface of extreme irregularity (McClean and Evans (2000)). Knighton (1998) introduces fractals as geometrical structures in the context of drainage basins, and he describes them as having irregular shapes and which are 'self-similar'. In this case, the fractal dimension (D) is a measure of the complexity, where the closer D approaches 2, the more thoroughly river channels fill the drainage area. Knighton points out that values close to 2 (Tarboton *et al* 1988) and in the range 1.5 to 2 (La Barbera and Rosso 1989) have been achieved from analysis exercises, but he points out that few networks are completely space-filling (or demonstrate similar values). Knighton also mentions that attempts to correlate fractals with Horton ratios and Hack's length-area relationships have not been convincing (Phillips 1993), and he concludes that for real-world) drainage networks fractals add relatively little to the probabilistic-topological approaches already expounded by many authors over the years, although he does give exceptions (Rinaldo *et al* 1992).

Fractals, therefore, are not the answer to synthesising everything geomorphological, but they do have their place in the analysis of real terrain, and they were found to be most useful for creating certain aspects of synthesised terrain. The ideal situation would be to utilise fractals in synthesised terrain in some 'balanced' way, thereby drawing on their inherent advantages without overwhelming the resultant landscape with fractal effects. This balance has been attempted in the research - from an initial perhaps over-enthusiastic rejection of fractals (Griffin 1987) to a careful but rigorous 'rehabilitation' of fractals in the later research, as presented in this thesis. The paragraphs below suggest how fractals can be introduced to help form 'primitive' surfaces, for example,

So far this chapter has examined two overlapping methods of terrain topology generation, each of which were considered in turn. These are the process response models published in a simple form by Griffin (1987) and the parametric models proposed by the author and adopted by the team working on the MOD-sponsored projects. Taken together, the techniques allow either 'generic' landforms to be created, or parameterisation and synthesisation of 'imaginary' real areas, with process-response and other methods used as refinements. The selected approach is shown in Figure 3.15 and it should be observed that the sequence was the first attempt - more refined methods were created after the detailed research on the various composite methods was completed (and after the GUI methods shown in Figures 3.7 to 3.10. Fractal landscape creation, although considered inappropriate as a major process on its own (McClean and Evans (2000)), is still worth

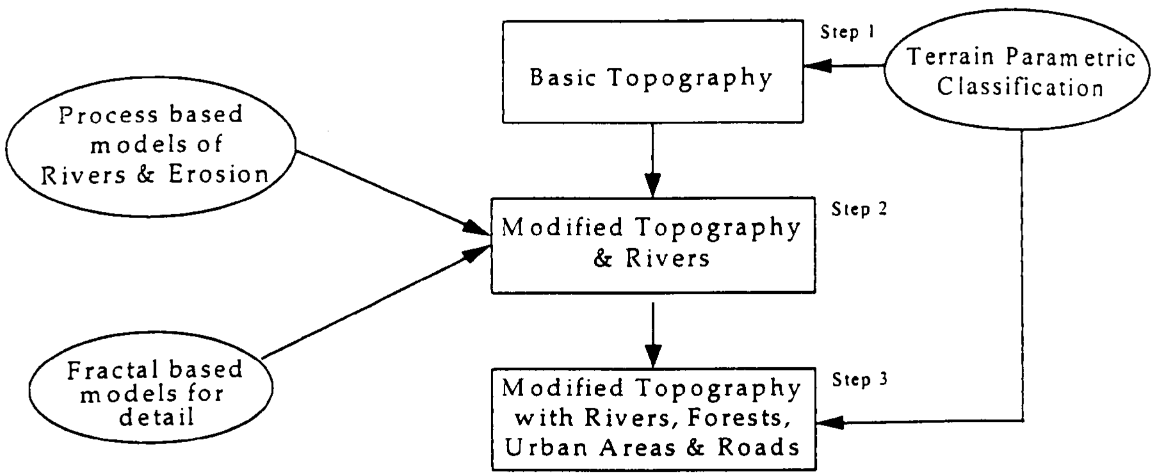


Figure 3.15 Selected approach (System Flow Diagram)

examining in a supporting role as a mathematical technique that can be used to create synthesised terrain.

3.13.1 Terrain Topology

Terrain may be broken down into a number of basic components. One such component is the 'terrain topology' (see figure 3.16). This is the term given to the 'primitive' terrain surface upon which surface water, culture and vegetation reside, in preference to 'topography', since the terrain is being treated as a mathematical surface. This part of chapter three describes the method adopted during the later stages of the PhD research, and adopted within the Geoforma software package used to generate the terrain topology component within the synthetic terrain. For this part of the methods chapter, some relatively complex mathematics was incorporated. Work on fractals and much of the mathematical derivation used in this part of the chapter has been based on work done by Mandelbrot and Van Ness (1968), Mandelbrot (1977, 1982), Franke (1982), Nielson and Franke (1984), Richards (1980), Schencke (1963), Voss (1985a, 1985b), Dold and Eckmann (1975), and Douglas (1986). A geomorphological 'check and balance' was provided by consulting standard works such as Shreve (1966) - for rivers - and 'standard geomorphological works' such as Schumm (1956), Leopold, Wolman and Miller (1964), Morisawa (1964), Pitty (1982), Fortey (1993) and others for general conformity. The author is also grateful to Shaun Heveron (unpublished work in preparation) for help with some of the equations. Work on deterministic uncertainty in landscapes was derived from Phillips (1994), and simulation and computer-aided geometric design was inspired by workers such Barnhill and Boehm (1983), and Csuri (1983). More traditional geographical approaches were provided by referring to workers such as J.C. Davis (1973).

3.13.2 Alternative mathematical approaches (FFT and Composite methods)

It was a requirement of one of the UK MOD Army projects (the STDRD project) during the mid-1990s that any synthetic terrain produced could potentially be based on a real-world region of the earth. There was also a request that the terrain could be 'edited' - in other words that it could be simply modified by a GUI user at a PC - in order to meet the needs of the exercise designer with consideration to the Army training objectives.

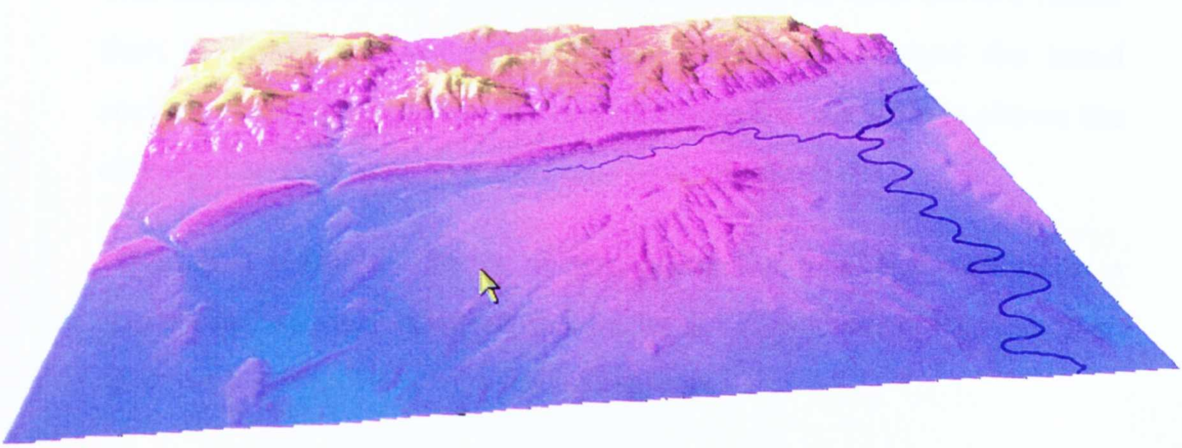
A number of methods for surface construction were considered including Fractals, Fast Fourier Transforms (FFT) and Wavelet theory. A comparison of these approaches is provided as follows: first, fractals can be made to look quite realistic and the fractal dimension of real-world data (i.e. a chosen physiographic region) can be calculated from elevation data. Although this approach is scalable (e.g. it can be used at almost any map scale or resolution) it has the disadvantage that it might not match the designers' needs. Moreover, there is no inherent relationship between fractals and geomorphologically-viable terrain - 'realistic-looking' is not good enough by itself (see 3.13).

It has been mentioned that Mandelbrot (1977), Peitgen and Saupe (1988) amongst others have shown that highly realistic *'looking'* representations for terrain and other natural objects can be obtained using affine fractal methods. Real-world terrain topology may be analysed to calculate the fractal dimension (D), which will lie in the region of $2 \leq D \leq 3$, and although it is relatively straightforward to generate a terrain with a similar dimension the actual location of peaks and valleys and their characteristics cannot be directly controlled. This is important to an exercise designer and so it was decided to adopt a slightly different approach. Fast Fourier Transforms (FFTs), on the other hand, can be made to produce realistic surfaces but are mathematically difficult to correlate with real world terrain elevation data. Some attempts to produce surfaces using Fast Fourier transforms, conversely, did not produce very realistic terrain, so there is an element of ambiguity here. Also Fast Fourier transforms have no inherent geomorphological relationship or validity.

Finally, Wavelets (the Wavelet Theory) can be used to analyse real world terrain. Relatively little has been done on Wavelet theory as some key works were not published at the time of the PhD research, and its uses in geomorphology are nor covered, although there is a web site (see chapter 2) and references (see Floater and Quak (1998, 1999)). These workers are more concerned with the computational and mathematical properties of wavelets, and although they do mention that synthesised terrain models could be used for flight simulation there is no 'geomorphological validation' - it is purely a mathematical approach.

Terrain topology may be divided into two components - that of a regional nature, and local fluctuations. What is considered to be "regional" and "local" is largely subjective and depends in part upon the size of the region being examined. Figure 3.17 shows a basic trend surface which was constructed prior to the more complex mathematical operations leading to a 'primitive' surface (Figure 3.16 is a sophisticated colour example of this 'primitive').

Figure 3.16. Illustration of Terrain Topology



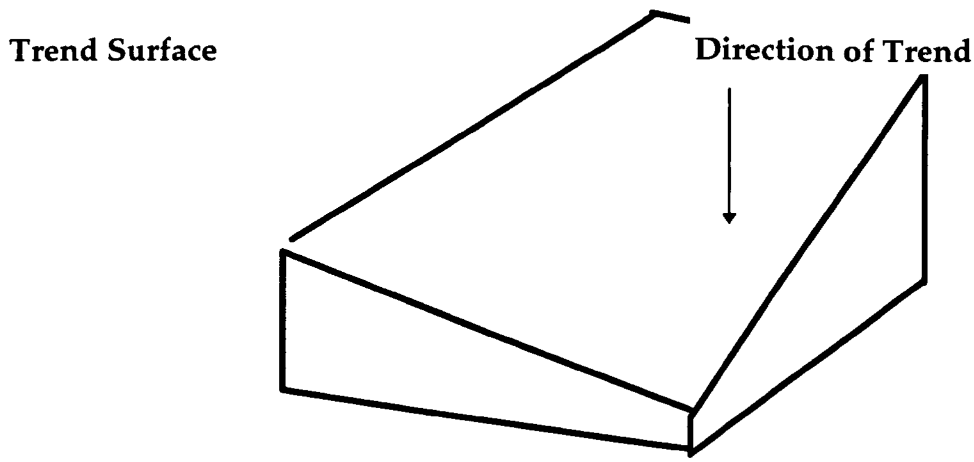


Figure 3.17 Trend Surface

Linear regression analysis was used on the elevation data obtain from real-world terrain to yield what might be referred to as a 'primitive' or a 'basic planation surface', upon which the 'local' fluctuations reside. This surface - the term 'planation' was chosen for convenience rather than to imply any geomorphological causality - formed the trend surface. Calculation of the plane coefficients for this surface allows the elevation at any point on the surface to be obtained.

Then it is simply a matter of re-creating the local fluctuations in a controlled manner using control surfaces. Thus the topology creation process is composed of the following steps:

(a) Establish the trend surface in accordance with analysis carried out on the terrain to be represented;

(b) Place control surfaces on the trend surface with a spatial distribution and shape which is characteristic of the region being generated. This is again in accordance with terrain analysis;

(c) Apply fractals to add realistic surface detail.

(d) Run process response models etc. if desired

3.13.3 Derivations

Mandelbrot (1977), Peitgen and Saupe (1988) amongst others have claimed that realistic *looking* representations for can be obtained using affine fractal methods which model object features using *fractional Brownian motion*. Although this may be a somewhat overstated claim, it is still worth examining their reasoning. This is an extension of standard Brownian motion, a form of 'Random-Walk', that describes the erratic, zigzag movement of particles in a gas or liquid.

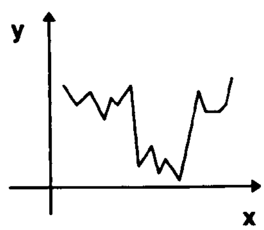


Figure 3.18 *Random Walk in the xy plane*

Figure 3.18 illustrates a random-walk path in the *xy* plane. Starting from a given position, a straight line segment is generated in a random direction with a random length. From the endpoint of this line segment the process is repeated.

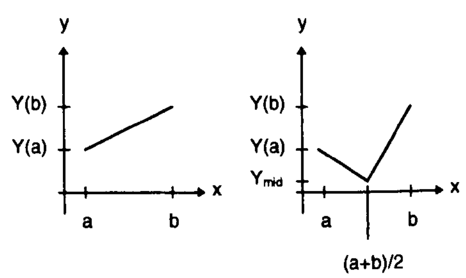
This procedure is repeated for any number of line segments, and the statistical properties of the line path over any time interval t can be calculated. Fractional Brownian motion is obtained by adding an additional parameter to the statistical distribution describing Brownian motion. This additional parameter defines the fractal dimension for the 'motion' path. A terrain surface can be obtained with a two dimensional array of random fractional Brownian elevations over a ground plane grid.

The 'ruggedness' of the terrain features can be varied by adjusting the fractal dimension in the Brownian-motion calculations. Fractal dimensions in the neighbourhood of D ≈ 2.15 can produce realistic looking mountain features, although no geomorphological validity is claimed and any 'apparent realism' may simply be a coincidence. As McClean and Evans (2000, p. 262 - 263) have said: *'the link between geomorphological concepts and Mandelbrot's ideas has been predominantly a visual one'.*

3.14 Random Midpoint Displacement

Fractional Brownian-motion calculations are time-consuming, because the elevations are calculated using a Fourier series, which are sums of cosine and sine terms. Although Fast Fourier Transforms (FFT) can be used, generation times are still rather slow, even though sometimes quite successful results can be attained (Figure 3.19). To overcome this, random midpoint-displacement methods, similar to the random displacement methods used in geometric constructions, have been developed to approximate fractional Brownian-motion representations for terrain. Although random midpoint-displacement methods were found to be faster to process than Brownian motion calculations there was no real basis - either objective or subjective - for judging one method to produce 'more realistic' looking terrain than the other.

Figure 3.20 Midpoint displacement method



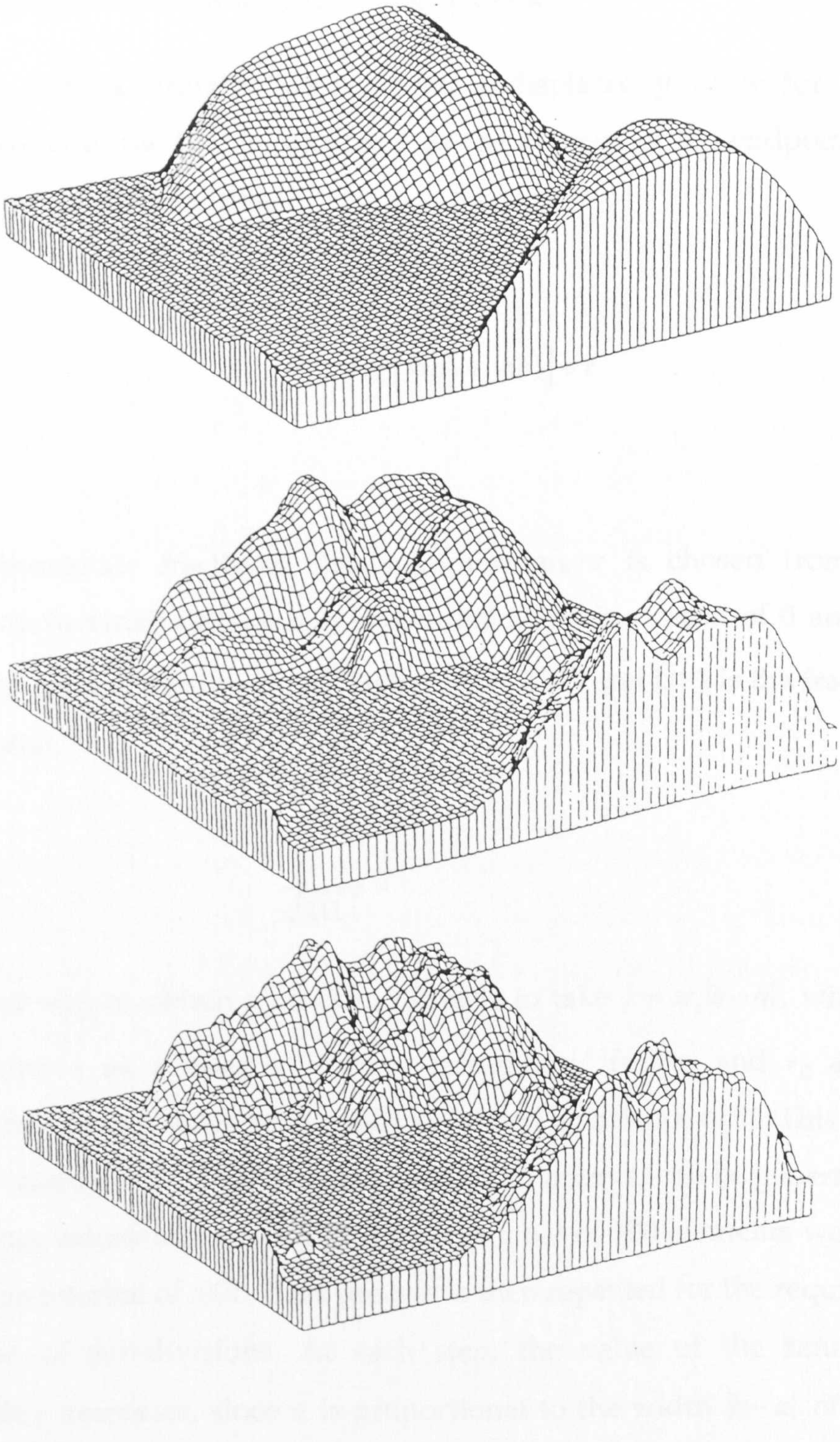


Figure 3.19 Synthesised terrain using Fast Fourier Filtering (FFT) technique.

Figure 3.20 illustrates the midpoint-displacement method for generating a random-walk path in the *xy* plane.

Starting with a straight line segment, a displaced *y* value for the midposition of the line is calculated as the average of the endpoint *y* values plus a random offset.

$$y_{mid} = \frac{1}{2}\left[y(a) + y(b)\right] + r$$

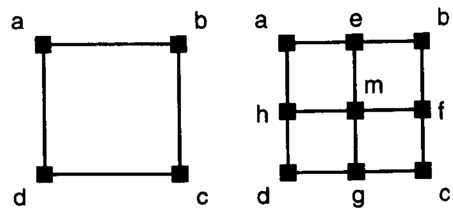
To approximate fractional Brownian motion, r is chosen from a Gaussian (normal) distribution shown below with a mean of 0 and a variance proportional to $|b-a|^{2H}$ where H = 2 - D and D>1 is the fractal dimension.

$$\frac{1}{\sqrt{2\Pi}}e^{-\frac{1}{2}x^2}$$

Another way to obtain a random offset is to take $r = sr_g|b-a|$, with a parameter s as a selected surface 'roughness' factor, and r_g as a Gaussian random value with a mean of 0 and a variance of 1. This has the advantage that a lookup table for a given interval can be generated to reduce calculation times e.g. a lookup table of 100 elements would given an interval of .001. This process is then repeated for the required number of sub-divisions. At each step, the value of the random variable r decreases, since it is proportional to the width $|b-a|$ of the line section to be sub-divided.

Terrain features can be created by applying the random midpoint-displacement procedures to a rectangular ground plane. Initially an elevation value is assigned to each of the four corner positions. Each edge of the ground plane is then divided at the midpoint position giving five new grid positions; see figure 3.21.

Fig. 3.21 Grid positioning method



The elevations at the midpositions, **e**, **f**, **g**, and **h**, can be calculated as the average elevation of the two nearest vertices plus a random offset. For example, elevation Z_e at midposition **e** is calculated using vertices **a** and **b**.

$$Z_e = (Z_a + Z_b)/2 + r_e$$

The random value r_e can be obtained from a Gaussian distribution with a mean 0 and a variance proportional to the grid separation raised to the 2H power, with H=3-D, and where D>2 is the fractal dimension of the surface.

The elevation **m** can be calculated using positions **e** and **g**, or positions **f** and **h**. Alternatively, Z_m could be calculated using the elevations of all four plane corners.

$$Zm = (Z_a + Z_b + Z_c + Z_d)/4 + r_m$$

This process is repeated for each of the four new grid sections at each step until the required number of sub-divisions is achieved, as follows:

Steps	No. of grid positions	No. of midpoints
1	4	2 x 2
2	16	4 x 4
3	64	8 x 8
4	256	16 x 16
5	1024	32 x 32
6	4096	64 x 64
7	16384	128 x 128

Table 3.1 Grid positions and midpoint numbers

Although these methods can produce highly realistic *looking* terrain areas, they do not generate surfaces with an inherent geomorphological validity. One way to control the placement of peaks and valleys in a fractal terrain scene modelled with a midpoint-displacement method is to constrain the calculated elevations to certain intervals over different regions of the ground plane. This can be achieved by setting up control surfaces over the ground plane. The nature and distribution of the control surfaces throughout the terrain would be controlled by results obtained from the parametric analysis of real terrain.

Once the fractal surface of the terrain has been generated, it will then undergo evaluation. Streams could be launched at designated points and erosion applied to the surface. Deposition can also be applied resulting in a realistic geomorphologically valid terrain.

In conclusion, fractals are disappointing as the sole or major agents of landscape generation, but they have validity for making primitive surfaces (on which further simulated 'erosion' and so-on can take place). However, they can be used in a 'controlled' form. Additionally, fractals may be used to help introduce 'noise' into the system in a more rational way than simply adding in a number between **+1m > n > -1m** on a random basis to create a sort of roughness or texture, as was done for example by Griffin and Gilmour (1981).

3.15 Super-Ellipsoids for generating primitive terrain features.

Although the methods described above can produce highly realistic *looking* terrain, they do not generate surfaces with an inherent geomorphological validity. One way to control the placement of peaks and valleys in a fractal terrain scene modelled with a midpoint-displacement method is to constrain the calculated elevations to certain intervals over different regions of the ground plane. This allows the geomorphologist to have more control over the surface being created, although of course there is no inherent geomorphological validity in the method alone.

This can be achieved by fitting the resultant fractal closely to a series of 'control surfaces'. It was decided for the this particular project to use Super-Ellipsoids, a member of the Super-Quadric class of shapes..

Super-Ellipsoids seemed to bear the most resemblance to those massive forms found in nature e.g. hills and mountains. They also have a number of inherent mathematical properties which can be exploited, for example the slope of the surface may be varied from concave to convex as required. The centre point (our notional peak) may be displaced as required. The Cartesian representation for a Super-Ellipsoid can be portrayed in many forms.

One example, given by Gray (1997) is expressed as follows:

$$\left|\frac{X}{a}\right|^{n} + \left|\frac{Y}{b}\right|^{n} + \left|\frac{Z}{c}\right|^{n} = 1$$

The corresponding parametric representation can be generalised as:

$$\mathbf{x = a\ cos^p\ \phi\ .\ cos^q\ \theta}$$

$$\mathbf{y = b\ cos^p\ \phi\ .\ sin^q\ \theta}$$

$$\mathbf{z = c\ sin^p\ \phi \quad where\ p = 2/n\ and\ q = 1}$$

The two exponent parameters p and q can be varied between 0.0 and 3.0 to allow us to control the profile of the shape, for $s_1=s_2=1$ we have a normal ellipsoid (note when q = 1 it is redundant anyway). The range of ϕ is:

$$\mathbf{-\pi/2\ to\ +\pi/2}$$

Whereas θ can take the range:

$+\pi$ to $-\pi$

The parameters a, b and r define the radii along the x, y and z axes respectively. We can then add rotation around the z axis by modifying the equations appropriately. For example, it is possible to rotate the ellipsoid about the z axis by manipulating theta (θ).

The real world terrain is then analysed in terms of control surfaces and a set of statistical parameters obtained. The control surfaces can then distributed using the parameter set onto the trend surface and their properties set accordingly. These would include, height, base dimensions, peak displacement and slope coefficients, (see figure 3.22). The operation is then able to set the fractal dimension and terrain conformity for the build, using parameters D and s respectively. The surface is then built using midpoint sub-division (as shown in figure 3.23). The resultant terrain matrix may then be saved into a number of formats including DTED or other desired DTM formats.

3.16 Sources

The work described above is based on derivations worked through by the author with help from colleagues (see acknowledgements), although some of the derivations have been drawn on from a wide range of source material including the following references: Mandelbrot and J.W. Van Ness (1968), Mandelbrot (1975, 1977, 1982), Franke (1982), Nielson and Franke (1984), Richards (1980), Barnhill and Boehm, eds. (1983) and Csuri (1983). Other authors included Voss (1985a and 1985b), Douglas (1986) and Phillips (1994). Some reference was also made to Schencke (1963), Shreve (1966), Davis, Ed., (1973), and Dold and Eckmann (1975) and Evans and McClean (1995) - (it should be pointed out that some of the later papers appeared too late to affect the algorithm development during the late 1990s).

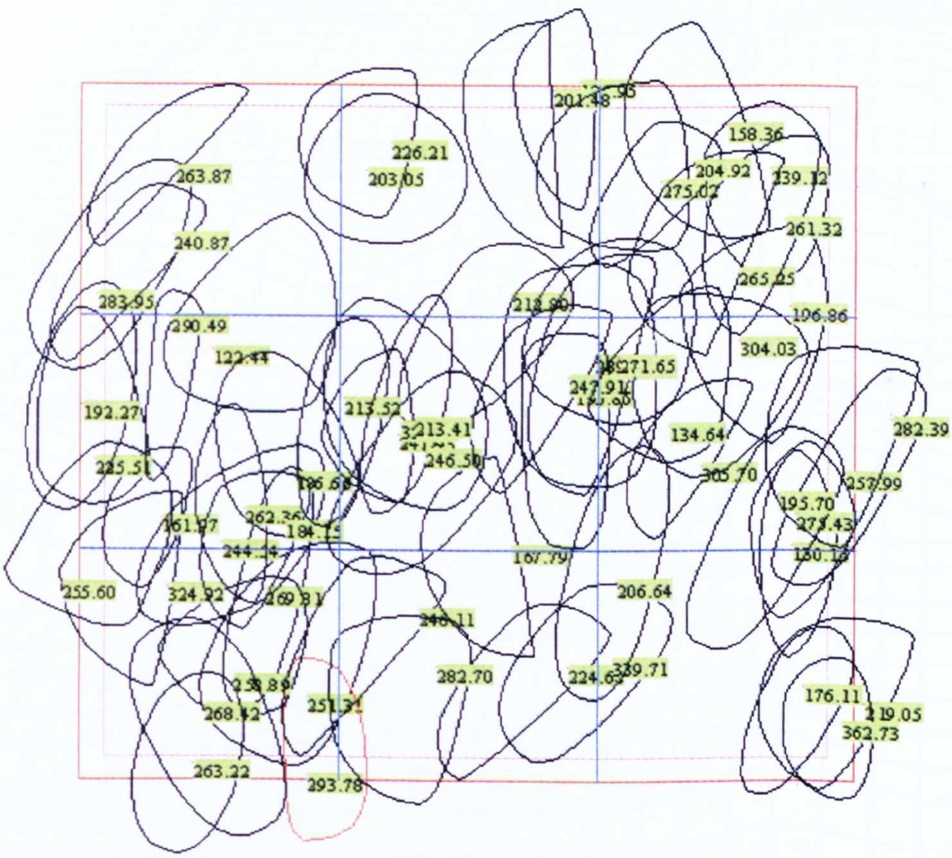


Figure 3.22 Superellipsoids as a control surface

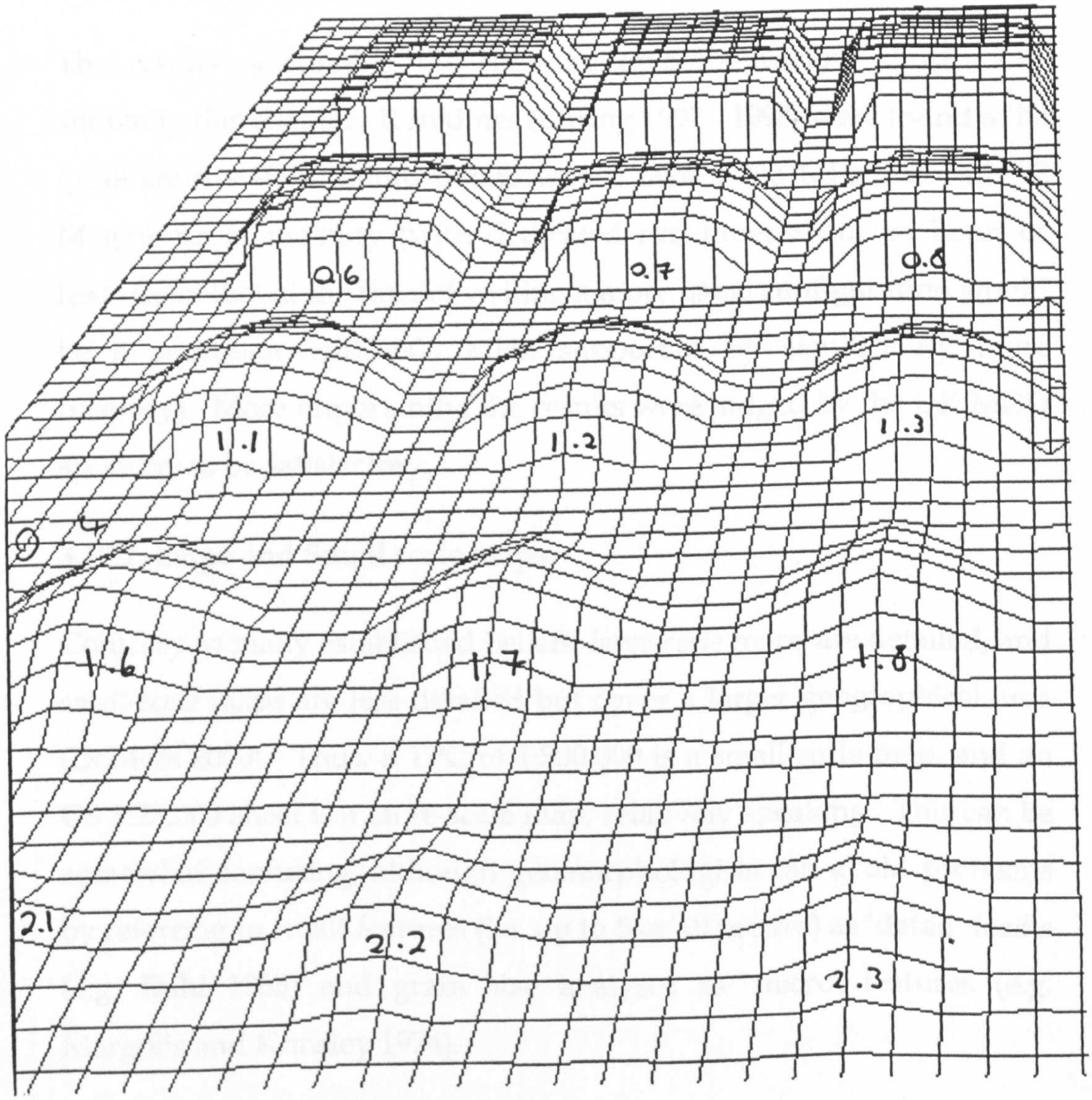


Figure 3.23 Fractal surface created by midpoint division

3.17 Identification and explanation of methods and terms

The following paragraphs identify and explain some of the key concepts used in the research, and indeed in mapping, GIS and terrain modelling generally.

3.17.1 Results - validation and iteration

The results of running the software give the various illustrations shown in this chapter. Run times (during 1997 - 1998) were found to be quite short - 100k datum points would take a 233 MHz PC with 32 MegaBytes of memory (with dedicated run time) about an hour, or less. (note that at the time of writing a more usual configuration would be a processor with 600 MHz supported by significantly more memory). More importantly, the results were judged by the UK MOD sponsors to be satisfactory.

3.17.2 Large and Small scale maps

Contrary to many established beliefs, *large-scale* maps are detailed, and *small-scale* maps are less detailed but cover a larger geographical area (DeMers 2000). Thus, a TPC of 1:500,000 is a small-scale map, and an OS 1:25,000 sheet is a large-scale map, relatively speaking. This can be somewhat confusing, although geomorphologists can avoid problems by referring to small features (i.e. up to 5 or 10 metres) as 'detail' forms (e.g. Dahl 1965) and grain size analyses as 'micro' features (e.g. Margolis and Krinsley 1974).

High resolution data sets tend to equate to large scale maps in the 1:5000, 1:10,000 and - conveniently for UK OS coverage - 1:25,000 scales. Different features will disappear or become irrelevant at one particular scale, and it is probably true to say that every terrain feature has an 'optimum' scale or resolution since most workers utilise the same size PC screens and map scales. For example: drainage ditches are difficult to detect at scales smaller than 1:25,000, whereas the boundaries of individual fields and houses may be portrayed quite well and accurately on 1:5000 and 1:10,000 scale maps.

Height data is interesting in its own right. Spot heights tend to be used at very large scale (where contours would be inappropriate or difficult to reconcile with the topography at such a detailed level), whereas contours are ideal indicators of relief at the 1:25,000 to 1:250,000 scale. There appears to be no established 'rule' or cut-off point - contours tend to be utilised at scales where they have 'meaning'. At smaller scales they can still be used, but whereas they are still successful and useful information components, they tend to be vague or ambiguous relief boundaries rather than accurate slope representations, as any look at a 1:500,000 map (see the Tactical Pilotage Charts - e.g. TPC No. D-2C covering parts of Scandinavia), where the trend of the land is indicated successfully. This is done with relief colouring and heights ***in feet*** at 50 ft intervals below 500 ft, and with a basic interval of 500 ft, combined with spot heights and (because of the usefulness to pilots) height information about towers and man-made structures. TPCs have been used extensively in the work, so a short note concerning them seems appropriate: they are superbly compiled small-scale navigational maps (or charts), which are published by Her Majesty's Government (HMG) and are based on Lambert Conformal Conic Projections (with the standard parallels and convergence factors printed on the map itself, along with grid north, true north and Latitude and Longitude).

All this is important. Every feature will have an ideal range of resolution or scale at which it can be useful information. Extensions beyond the useful range makes clutter at large scales and meaningless microscopic shapes (and clutter) at smaller scales.

3.18 Geomorphological (Process-Response) Modelling

An important part of the methods or 'toolset' of the research is that which deals with geomorphological models - mostly landform process and process-response modelling. These algorithms - coded as procedure calls in the Geoforma software - are described in detail in the four chapters that are concerned with the 'results' - or exercising the models (Chapters 4, 5, 6 and 7 - which cover rivers/slopes, upland areas, granite areas and coastlines respectively), and are not described individually in this current chapter.

3.19 Presentation

An important part of mapping - even digital mapping - is of course presentation. The methods used in this thesis borrow from a range of techniques available to digital terrain users, and include:

- Geographical Information Systems (GIS) technology
- Automatic and computer-aided Cartography
- Manual cartography

It must be stressed that the thesis does not attempt to present 'state of the art' 3D rendering etc., as even as recently as the mid-1990s this was not available at the quality currently possible. The study used the tools that were within the resources and budget of the research. Even this gave a wealth of products and systems that were used to present data. Naturally some data sets are shown not as maps but as 'traditional' statistical diagrams (histograms, scatter diagrams, graphs etc.).

Also there are different levels of sophistication available to the PC user depending on the circumstances; indeed one can contemplate the design process that underpins cartography and symbology at a basic level (DeMers 2000). Taking for instance the need to produce 2D and

3D map presentation, then such design tools can range from simple 'cheesecloth' or wireframe 3D surfaces to fully-rendered 3D surfaces with shadows, reflections and texture (see Figure 3.2). Even the illustration shown has been greatly improved since the writing of this thesis, and should not be taken as an example of the 'state of the art'. Some of the 3D diagrams have been drawn semi-manually, or more recently with the help of various computer tools such as POVRAY or one of the many GIS packages available (Holmes 1984, Kraak 1993, Jackel 1997).

Two-dimensional (normal or 'traditional') maps also vary considerably, from the wealth of detail found in - for example - an OS 1:50,000 map, where a 'balance' has been struck in order to portray topography, roads, ancient monuments, rights of way, land use etc. to special maps, such as geological maps and soil maps.

Some maps are composed of contours only, as DEMs tend to require basic relief information, although rivers and streams are often superimposed. Similarly, coastal area maps may show 'dynamic' elements such as the relative high and low water marks in tidal areas (the littoral zone). Presentation can also utilise remote sensing and photographs. The research used photographs in some exercises (see Chapters 6 and 7) both as oblique and plan aerial photographs and as deliberate presentation of complex landforms (such as granite boulder fields) which are difficult to see from the ground. In some cases, photographic views of a landscape from a vantage point may be compared or contrasted with Geoforma products. Satellite imagery is another useful tool, although it was not exploited as much as perhaps it might have been in the original research.

Finally it is tempting to provide a detailed discussion of the various GIS tools used or considered as part of the research. Although the GIS capabilities are employed and mentioned when necessary this temptation is resisted: not only is it beyond the scope of this thesis, but there are too many products for an easy comparison to be made. Moreover, only two or three products were available to the author at the critical times during the research, and these were used as tools. GIS - like many other software tools - can be taken too seriously and are only merely a means of achieving a goal.

3.20 The Geoforma software suite

3.20.1 The software: Geoforma Structure

The Geoforma software has been built in a modular fashion, so that individual programs or modules correspond to particular functional areas. The structure is controlled by a 'master' module, and while some parts - such as the GUI (interactive elements) interface directly with the user, other modules are 'transparent' and process complex algorithms without the need for the user to become involved, once the choices or options have been selected correctly and the program is set running. The salient points for the design and implementation of the latest software suite are listed as follows:

- **Required to run under the Microsoft® Windows Operating Systems (particularly NT version 5.n and later)**
- **Developed using Object Orientated (OO) Techniques to minimise risk (as the tools were intended for OO Design)**
- **Code developed using Microsoft Visual Studio 4 and 5**
- **Written in C++ and using the Microsoft® Foundation Classes™ (MFC)**
- **Facility to use Structured Query Language (SQL) for database access**

- **Extensible architecture**
- **Uses OLE/ COM technologies to facilitate reuse**
- **At the time of the research runs on top-of-range Pentium PC as a stand-alone package.**

3.20.2 The software: Geoforma functionality

The Geoforma software has already been described as highly interactive suite of programs which allows a user to manipulate a 'form' or window to select options, or can run a software tool or device called a project 'wizard' to create a new landscape file for a special purpose (e.g. a new set of terrain outputs). Figure 3.24 shows a rough outline of the main modules in Geoforma. Some (like SCISSORS) are acronyms (i.e. Synthesised Coastline Initialisation, Synthesis, Storage and Object Representation System) whereas others modules are not named for any reason other than that they needed to be distinct and differently-named with respect to the wide range of software library function calls available - such as in GIS systems or other simulators. The Geoforma GUI software has been programmed to ask the user questions about the geographical area - located in terms of options based on Grid References (GR), Grid Co-ordinates in **(x,y,z)** space - or Lat./Long., and 'hilliness' (or the intensity of the relief) and other factors. After processing the end result is a Program File, which is stored in a library. Because the software is based on Object-Oriented Design (OOD) and the object-oriented paradigm generally, each new file can be regarded as a 'compound document' in object terminology. A compound document is - effectively - a document that is composed of several different parts, such as text, numerical data, images and so-on The file will have attributes or components, and will allow inheritance (an OOD term implying the propagation of associated attributes and related features), should this be needed (Brown 1991). For example, a component exists for each area thus:

- Component for fluvial erosion
- Component for infrastructure etc.

Therefore all the components will cumulatively create the overall simulated map. In keeping with earlier work, the acronym Area of Responsibility (AOR) is term used - in this case the AOR is the size of the tile (the area of the map) in metres and it also defines scale and origin, as well as essential positional data such as Lat./Long. or grid reference origin. An AOR can be created from a new region by means of a map sheet, or (and this has been of particular interest to DERA) the user can load in DTED and DFAD format data. This chapter is, of course, concerned with the methodology and software that allows the simulation of general aspects of the landscape - the geomorphological (erosional) components as well as human habitation effects such as for the creation of settlements, known collectively as 'culture' or 'infrastructure'. A Project file may or may not have certain components - e.g. it may not have river components (which can be added or deleted). Components are represented physically by 'soft buttons' (programmed switches selected by the mouse, for example) along the top of the form or window that invokes existing components. Each project file has basic components or attributes (title, security classification etc.) - but it should be remembered that these are attributes of the *project* and not of the *map*.

3.20.3 Manual Control

Part of the software allows the user to invoke the terrain topology component (macro-relief) - known as control surfaces - which can be moved around or otherwise manipulated manually. This is useful if a user wants to define a 'killing ground' or some other specialised feature for a military scenario. The downside of this is that the user is interfering with the computers' interpretation of 'correct' terrain, and an error message will result. This does not necessarily 'invalidate' the terrain, but it does warn the user that manual interference may have some effect on the integrity of the output. However, this can be overcome either by setting limits that do not compromise the terrain appearance or by providing warning messages to the user. The limits are set by allowing the user an agreed 'degree of freedom' - say 10% plus or minus on whatever parameter is being manipulated. Thus if a slope becomes 10% greater than the setpoint, an error message can be made to appear, or the user can be prohibited from undertaking the action (i.e. the 'commit' is not allowed). Alternatively the user may be allowed to continue with a warning that he or she has 'compromised the integrity of the terrain'. Warning messages may seem to be self-explanatory, but they must be carefully composed to inform the user. It is suggested that three thresholds of error are used: trivial or low risk (*no or little effect on terrain integrity*), some risk (*danger of effect on terrain integrity*) and finally: serious or high risk (*danger of compromising terrain integrity*).

The user can also change 'mode'. This means that features such as *mode,* or *resize, move,* or *change width* are all interactive. In true Object terminology and approach there is a *Property Sheet* for each component. A property sheet contains information about the attributes of an object - an example away from the terrain subject would be a property sheet about a printer icon. This might state the name and type of printer, as well as which network it was attached, and details such as pages per minute, colour capability, physical location in a building etc.

A user can also define a *trend surface* - which is a generalised plateau or area of terrain. (A real example might be the slopes leading from the tors of Dartmoor in Devon, UK, down to the edge of the moor where the countryside changes from planar granite with outcrops of rock to more undulating farmland). In the PhD research project the surface is also known as the planation surface. This is a term used for convenience, as a true planation surface would be (for example) an area of flat or slightly-sloping ground recently emerged from the sea due to emergence or uplift. The user can therefore 'set up' the planation surface primitive or can set the vertical datum (with respect to Ordnance Datum - OD and height above mean sea level) - in order to relate to the so-called 'fractal build', so it is in effect creating a more complex surface with a stochastic element. If the user requires vertical exaggeration then that would come later as a function of the display rather than of the fundament creative process. This is sound and a proper practice, and matches the design philosophy inherent in OOD and within the research generally. A regional slope may be added if required, as this could help the simulated downward path of a river exercise, although this may not fit in with the areas or even the concepts being modelled (see chapter four).

Fitting a Brownian Fractal is done by repeating midpoint divisions as described above and in the chapter on creating upland topography. In summary a terrain surface or planation surface is created - this can be tilted, curved, flat etc. Then superellipsoids are created, where 'positive' values are hills are 'negative' values are depressions. Midpoint subdivision is then used to help fit a fractal to this control surface - producing a accurate if rather coarse landscape on which more subtle variations can be operated. The terrain conformity value (TCV) is established, and this determines the extent to which the fractal 'fits' the surface and the superellipsoids (which themselves are part of a superquadric set). Low TCVs give the fractal a degree of independence (i.e. not a close fit), whereas high TCV values force the fractals to fit closely.

The topography may be further adjusted by interpolation (linear at the moment) so one obtains a coarse mesh per fractal of basic terrain topography. Naturally all this work is aimed at producing a 'primitive' on which process-response models or other simulations can be invoked for extra realism or to achieve some desired effect. The initial results, allowing for the leading edge state of the research, are reasonably convincing and far superior to previous efforts. The user is rewarded by a accurate-looking surface appearing on the screen. This, of course, is the primitive surface before rivers or other erosion is allowed to transform it, but even so, there are elements inherent in the pictures (not all are successful) that appeal esoterically. Also, it must be stated that the original MOD-sponsored programme of work was never set up to produce perfect imaginary terrain with the intention to 'fool' cartographers, geologists, hydrographers and geomorphologists - the point was to produce terrain that would be very realistic yet could be manipulated. Terrain statistically and subjectively derived from parts of the world on a 'dial-up' basis would also, of course, be most useful.

Indeed, after some years of MOD-sponsored research there is something of a 'chicken and egg' conundrum, since terrain must have been created in the first place by erosional or depositional agencies, and yet further erosion may take place as if it were a virgin landscape. Actually this is not problematic for Earth Scientists, who are used to be confronted by a question along the lines of *'when did this surface originate?'* or 'is this surface relic?' The theme underpinning all algorithm and software development on the project has been to justify each action with Earth Science 'possibilities' - there are no special cases and standard works quoted in other chapters have been invoked as each problem is encountered and solved.

Then, if required, the user can further adjust the coarseness or tuning to achieve a finer mesh. The fractal dimension is important, as manipulating the value the user can make the surface 'noisier' or more perturbed. It has already been pointed out that certain D values (e.g. D = 3) will give a spectacular landscape like the mountains of the moon or some alien world - and it is this 'uncontrolled' use of fractals by non-geomorphologists to produce unlikely landscapes that has possibly caused some unease among Earth Scientists over the years. However, fractals are now better understood and as a result are tentatively harnessed to the requirements of the research project. Fractal dimensions thereby provide the user with an interesting tool for trial and error. Indeed, experimentation and a gradual familiarity with the system, which is fast and interactive, is a great advantage, when compared to terrain building batch runs of the 1970s and 1980s using mainframes, which could take hours, even days.

3.21 Erosion and timescale - general observations with respect to the modelling

This chapter is concerned with the methods and techniques used in the thesis and the programmes of work that make up the research being described. The simulation of erosion is clearly important to synthesised terrain. Interestingly, erosion can be 'inferred' by adopting the terrain classification methods described above, and of course the mathematical models already described are intended to simulate various landforms that have suffered erosion. It is important to outline the types of erosion in a general context - the following points apply to simulated erosion wherever it may be reported in this thesis. Erosion takes place in a variety of climatic and environmental 'scenarios', including:

- Beach/coastal erosion
- Desert landforms
- Glacial (valley or local glacier)
- Continental ice sheet
- Subglacial erosion effects (e.g. meltwater)
- Wind erosion - 'normal'
- Wind erosion due to special conditions (storms, winds associated with glaciation effects, etc.)
- Fluvial erosion (various forms)
- Runoff (water flowing down hills and fields etc.)
- Other specialised (e.g. man-made, ditches, embankments, animal tracks, Deforestation, poor agricultural management etc.)
- Chemical decomposition of rocks

Naturally all the above can occur in compound form - so in deserts continuous wind erosion can be combined with a rare flood : this is the way that apparently dry and relic features such as Wadis - desert river channels - come 'alive' periodically. Indeed, most areas of the world demonstrate this 'classic' mixture of continuous and catastrophic processes, although this was found to be difficult to simulate in any generic, satisfactory way.

The next point worth mentioning is **timescale**. Time is important in any simulation, but this research has not been concerned with the 'classic' chronology of geomorphological and geological studies. Time is simply incremented in the simulation as 'events' or steps.

Older features have, however, been considered. They can be placed into three categories:

- The general outline of the continents and the ocean floor - which is part of a long and ancient process of crustal activity (plate tectonics and continental drift).
- Those features that are simply ancient because they are large and may be associated with hard crystalline rocks - such as mountain cordilleras, although even then some landforms may be recently eroded - examples are the deep glacial valleys in Norway and North America - which are comparatively recent features cut into ancient rocks.
- Those landforms that are ancient features (called 'relic') that have been recently exhumed in a realistic position (e.g. a relic marine beach would not be credible unless it was relatively horizontal), often causing problems even to experienced Earth Scientists as to their age and origins.

None of the above are simulated directly in this thesis, although they are recognised and acknowledged for the sake of completeness. To summarise, this thesis does not attempt to model very long timescales, even those with the occasional catastrophic event, and such features can be disregarded. Indeed the software that supports the synthesised terrain would not be able to simulate such features unless special modifications to the algorithms, the parametric methods and the end-product Geoforma software is carried out.

Finally it should be mentioned that whereas time should be a key factor in any scientifically-conducted simulation, whether it is merely inferred, or used to control the simulation (as in continuous simulations where a 'clock' is set in motion, or event-based/step-change simulations where time 'jumps' from event to event accordingly - see Fishman (1978)) it is not the intention of any of the Geoforma work to use absolute time. The whole area of simulations and systems behaviour is vast (Beishon and Peters (1977), and although some basic 'simulation' or 'modelling' forms the core of much of the synthesised terrain work, at a strictly academic level much the conceptual side lies beyond the scope of this work. In Geoforma, time is inferred, although one could claim that the process-response models are 'event-based'. However, it should be explained that there was never any intention to model even the process-response aspects in - for example - 1000 year intervals. The concepts of uniformitarianism and catastrophism have already been introduced - suffice to say that for the sponsored parts of synthesised terrain modelling the users had no interest in (and indeed vetoed the use of) any kind of timescale 'clock' in the model. This was not found to be problematic, since one would have to justify and rationalise 'synthesised timescale' when the problems of validating synthesised terrain are themselves formidable.

3.22 Conclusion of this Chapter

This Chapter is significant in terms of laying out the various methods used throughout the research. It must be understood that the methods started off in the late 1970s as limited research tools, partly because of lack of time, IT sophistication and resources. During this period some basic concepts, such as interpolation, DTM and DEM formats, 3D viewing, contour to grid to contour transformations and simply mathematical models (e.g. eggbox terrain) were used by the author, who began to realise that such techniques were becoming widely used by workers in academic and other institutions.

As far as this research is concerned, the 1990s was a period where the greatly improved IT resources, the advent of GIS and presentation tools and the generally improved capability of researching geomorphological synthesised terrain was utilised, albeit constrained at times by the sponsors' requirements. These included the need to supply realistic yet artificial maps of real world areas and general 'imaginary' landforms for military training and simulation purposes. Although the geomorphological side was at first somewhat limited, the author was encouraged to contribute input on algorithms, with specific landform types (coastal areas, uplands, river basins etc.). Also, real world physiographic regions were selected.

This in turn led to a massive upgrade of the author's simple river model program GEOFORM (Griffin 1987) to a more sophisticated software suite called Geoforma (see Figure 3.24), with the addition of many new or rewritten modules to add more sophistication to the synthesised terrain programme in general. This software also allowed 'true' topography and human infrastructure to be included. In tandem with this, the author helped undertake a research programme into the various comparative methods:

- Terrain evaluation (classification and parametric analysis)
- Fractals, Fast Fourier Transforms and Wavelets
- Other mathematical methods (functions of $z = f(x,y)$, interpolation etc.)
- Process and process-response algorithms for geomorphological theory
- Selection of real world areas (by means of terrain classification)
- Detailed models of features (Catenary curves for pylons, roads etc.).
- Combinations of the above

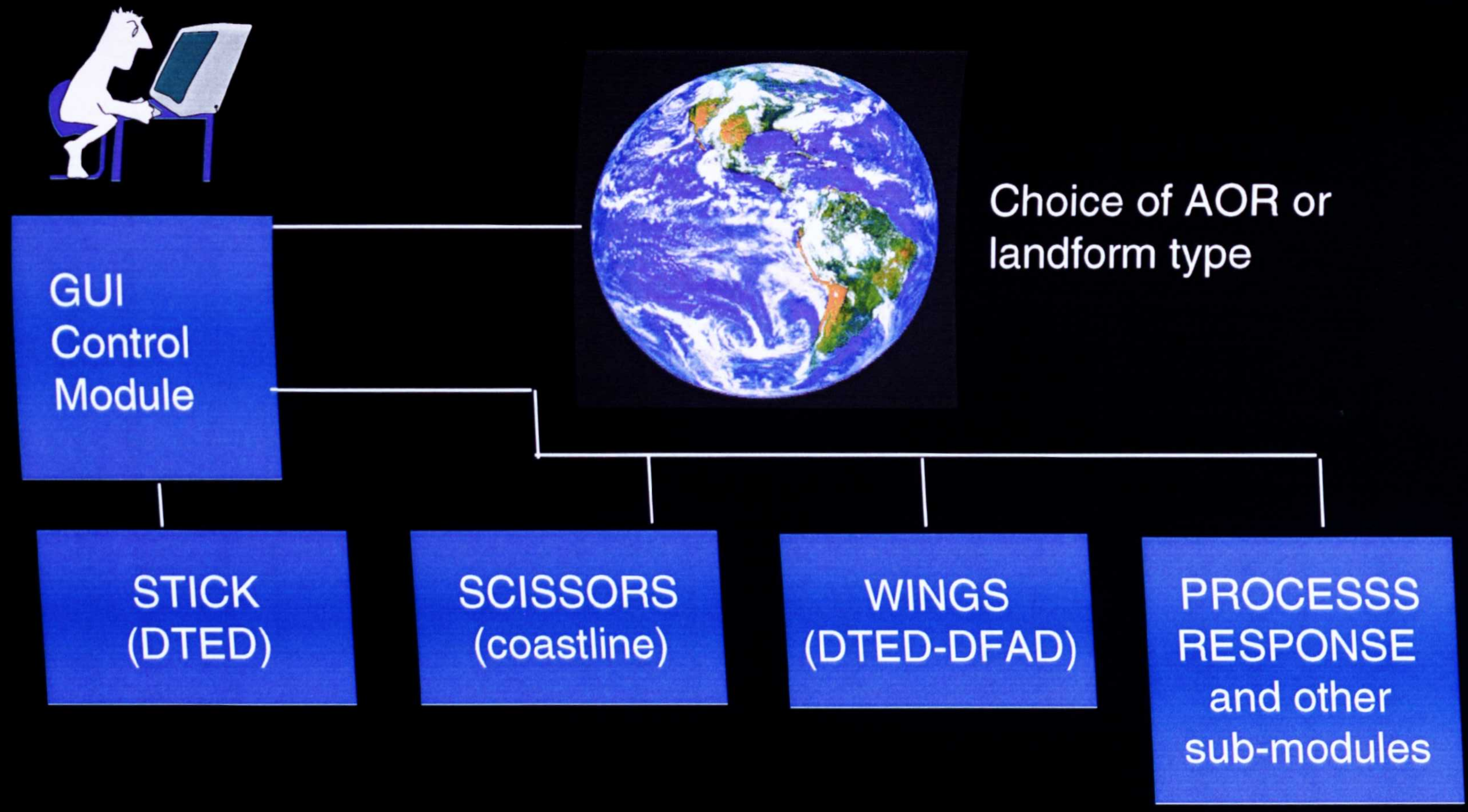


Fig. 3.24 Geoforma - Structure of software modules

- Management of the data (creation, modification, storage, display, deletion etc.) in a 'database'

- Use of GIS to render 3D views and produce 'realistic' maps.

Put together, these methods represented a powerful toolset. Two trial examples of composite methods are shown in Figures 3.25 and 3.26. Figure 3.25 is a somewhat 'blocky' attempt to create synthesised terrain of southern Germany (with contours at 50m intervals as an inset) whereas Fig. 3.26 is another trial 3D view using super-ellipsoids - the figures demonstrate that the project was moving towards the realism it sought but that there was still some way to go before really valuable or realistic results were obtained.

The consultant (Professor Petrie) requested by one MOD project to monitor geomorphological viability pronounced the resultant synthesised terrain progress satisfactory, although he retired before he could publish any written results testifying to this. However the author is grateful for his input and kind words. Finally, the advantages and disadvantages of the various methods are summarised:

(a) Parametric methods

Advantages

- The real terrain is statistically captured enabling real-world areas - even in hostile regions - to be simulation inputs for Army training.

- Terrain synthesis is simplified, the need for the understanding of detailed models giving rise to terrain characteristics is avoided.

Disadvantages

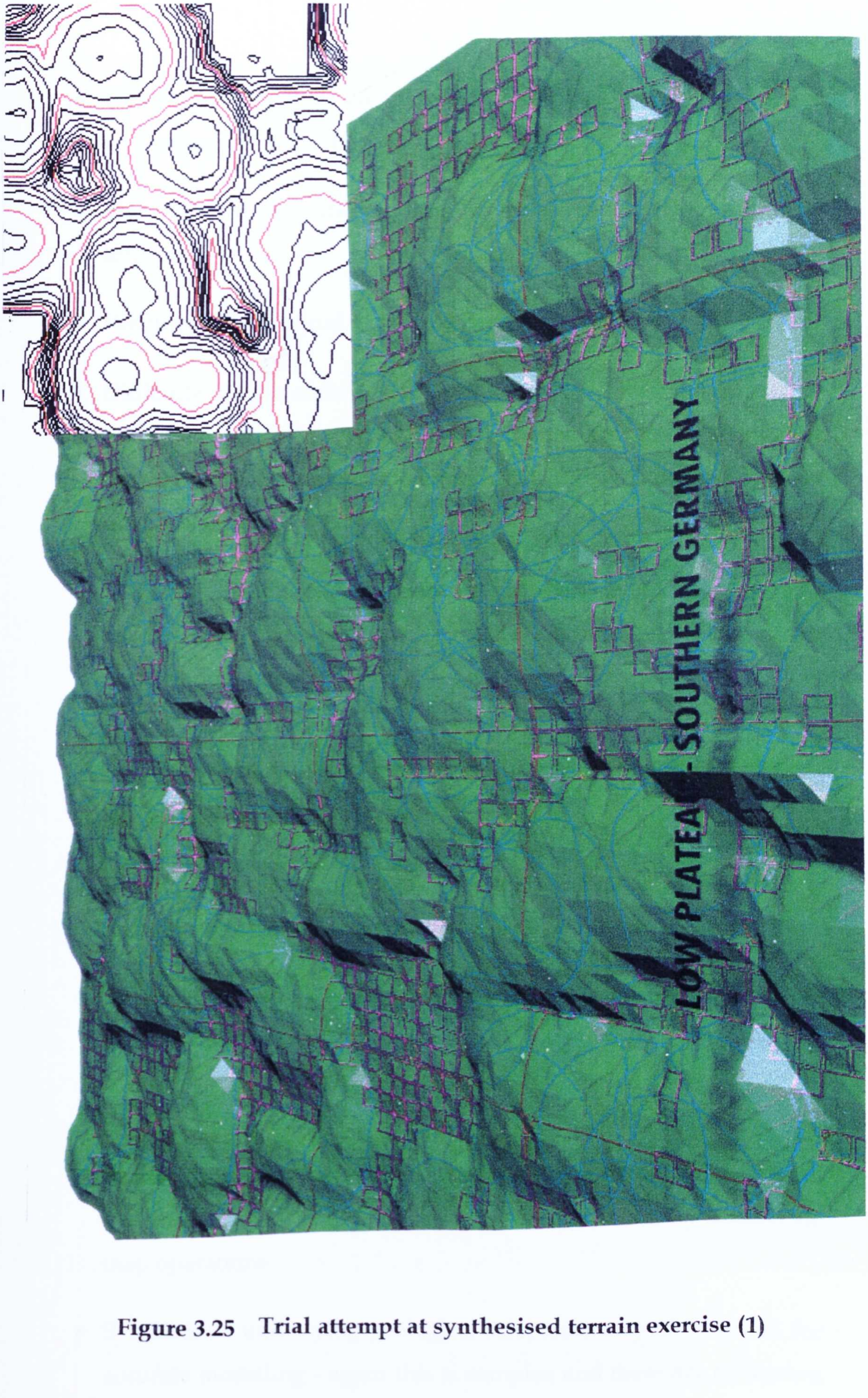


Figure 3.25   Trial attempt at synthesised terrain exercise (1)

- Terrain topology is complex, and a considerable number of parameters are required to describe it effectively

- The statistical measures required for synthesis vary from terrain to terrain

- Resources are required to analyse maps

- Difficulty in generating synthetic terrain to meet the particular needs of a training exercise, the operator requires understanding of the meaning of each parameter and their inter-relationships which may be subtle

- Statistical validation of resultant synthesised terrain becomes suspect, since one is simply reading the output or 'reflections' of the input parameters.

(b) Process-response models (Erosion)

Advantages

- Resultant terrain topology can potentially be made highly realistic and have a reasonable geomorphological validity or 'integrity'

- There is a wealth of literature and models available to help the geomorphologist

Disadvantages

- A full understanding of the terra-forming processes are required, and these may be extremely complex even at relatively small-scale map operations.

- Synthesis of underlying geological structures may be required for accurate modelling - again this is complex and there are no known precedents for such detailed synthesis modelling

Figure 3.26 Trial attempt at synthesised terrain exercise (2)

- Uncertainty about when to bound the model - there are no precedents and many 'rules' were made by trial and error.

(c) Fractals

Advantages

- Fractals may be used - with care - to help create topology which can then be used to create more realistic DTMs, either by applying geomorphological models or some other treatment.

- Synthesising realistic terrain topography through controlled fractal geometry methods and erosion models is certainly an improvement over the 'tilted plane-constrained random walk' approach used previously by the author and published in 1987.

- They can take advantage of literature on scale and existing feedback models, and can be used as components of fluvial landscape systems.

Disadvantages

- Disadvantages are that fractals cannot solve everything - there is an element of 'fashionability' about fractals - sometimes they are in favour and other time not; which tends to obscure their real usefulness. This claim can be made for other mathematical methods (e.g. FFT), although it is fractals that appear to have captured the lion's share of literature and research work.

- Also, despite claims for self-similarity and so forth, there appears to be no real evidence for a *generic* relationship between geomorphological phenomena and fractals (McClean and Evans 2000).

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CHAPTER 4 : DRAINAGE BASINS: DISCUSSION AND POSSIBLE SOLUTIONS FOR THE GEOFORMA STREAM MODEL

Chapter 4

Drainage Basins:

Discussion and possible solutions for the Geoforma stream model

4.0 INTRODUCTION

4.1 Objectives of this chapter

This chapter describes, discusses and supports the algorithms and approaches to introducing simulated fluvial processes into the Geoforma software. The work is concerned largely with the constrained 'random walk' of one or more streams over a primitive surface, which establishes the drainage pattern and, by implication, the relief (since extrapolating the relief or DEM from the streams refines the primitive surface relief and denotes erosional and depositional features such as flood plains, valleys, spurs and interfluves).

However, before the details of the 'process-response' software and algorithms are identified, it is important to gain an understanding of the drainage basin as a 'fundamental spatial unit' (Chorley 1960). Several geomorphological topics need examining in order to contribute to the Geoforma program, and these are based on several authors. Typically, the elements (following broad criteria laid down in Knighton 1998) are:

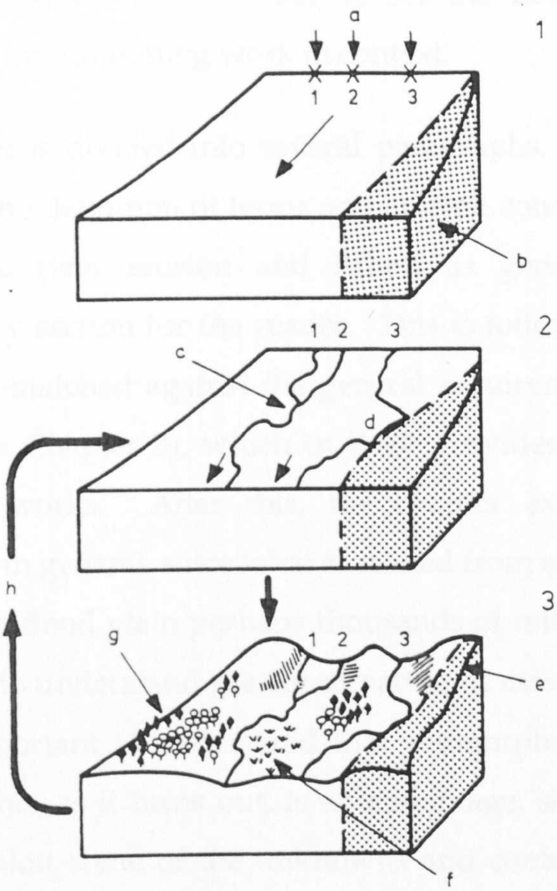
- **Network Analysis** including drainage density, drainage network composition
- **Hillslope Process,** including slope hydrology, water erosion processes

- **Channel initiation** (overland and subsurface flow)

- **Network evolution** including some existing models

This is an non-trivial task, particularly where there are logical difficulties with 'boundary' conditions, such as where simulated streams flow across unknown or unprepared terrain into 'dead-ends'. Early published work on synthesised fluvial terrain by the author (Griffin 1987) postulated streams 'running' down a flat, tilted surface (see Figure 4.1 - this figure is derived from this paper). This model took into account geology (which 'weighted' the stream away from more resistant lithologies) and could be used in a single-cycle or a multi-cycle mode. The problem with the multi-cycle mode was that sometimes the streams went into 'cul de sacs' - this problem is considered in this chapter. Indeed, this is not a new problem, Garbrecht and Martz (1996) considered the so-called 'D-8 method' (a relatively simple flow routing method utilised by Fairchild and Leymarie (1991)). The simplistic view used in the author's research worked well for demonstrating the algorithm, but it was considered inappropriate for the current work, where primitive surfaces produced by various methods - particularly parametric analysis representing real-world physiography - would already exhibit relief, and so planar surfaces would not be consistent with the desire to model particular regions or types of terrain. A similar piece of work (Dunne 1980) showed a rapid tilt to produce stream development by means of springhead sapping (Figure 4.2), although this was based on 'seepage erosion' or groundwater. It was decided not to apply this model since the code for the Griffin 1987 model already existed - and both used a tilted planar surface as a starting point.

This chapter lists the main areas of work on modelling fluvial stream path choice and the modelling of subsequent erosion in what are called throughout this thesis 'process-response' models. The text also



Theoretical sequence of synthesized terrain evolution.

Key:

Phase 1: Primary surface and other parameters initialized
a—Stream entry positions established on highest surface edge.
b—Band of resistant rock defined.

Phase 2: Stream patterns established by random-walk process.
c—Stream 1 becomes tributary of Stream 2.
d—Stream 3 avoids resistant lithology.

Phase 3: Slope profiles established.
e—Additional slope retreat on steep ground to simulate instability.
f—Evaluation of terrain features and attributes.
g—Wooded areas established on 'game-of-life' basis.
h—Feedback loop to Phase 2.

Figure 4.1 Theoretical sequence of synthesised terrain evolution through fluvial erosion

explains the differences between weathering and erosion, and some of the limitations and sources of information which have constrained (or helped) the work. Thus there is a 'general case' explanation of fluvial dynamics and erosion in order to set the detailed algorithm and subsequent programming work in context.

The chapter is divided into several paragraphs. The first paragraphs deal with the definition of terms and erosion concepts, and then go on to examine river erosion and runoff as general concepts as an introductory section for the reader. This is followed by the proposed algorithms matched against the general requirements for synthesised terrain (see Chapter 3), which in itself provides a summary of how Geoforma works. After this, the chapter examines erosion and deposition in general, since what is eroded from a mountain valley will end up in a flood plain perhaps thousands of miles downstream. It is important to understand the conservation of mass in these affairs, just as it is important to understand that geomorphology is not an exact science. This, as it turns out, is an advantage, since the research was able to exploit some of the unknowns and controversies in the earth sciences to achieve a desired result, without compromising any 'scientific' rules.

4.2 Background

This synthesised terrain PhD research project reached the stage where the algorithms and derived software were becoming more sophisticated and functionally rich, thereby satisfying the original requirements of the research. For example, the planar surface used for the constrained random walk (Griffin 1987) was replaced by a far more complex algorithm allowing a stream to 'wander' over a primitive surface which could exhibit relatively complex relief.

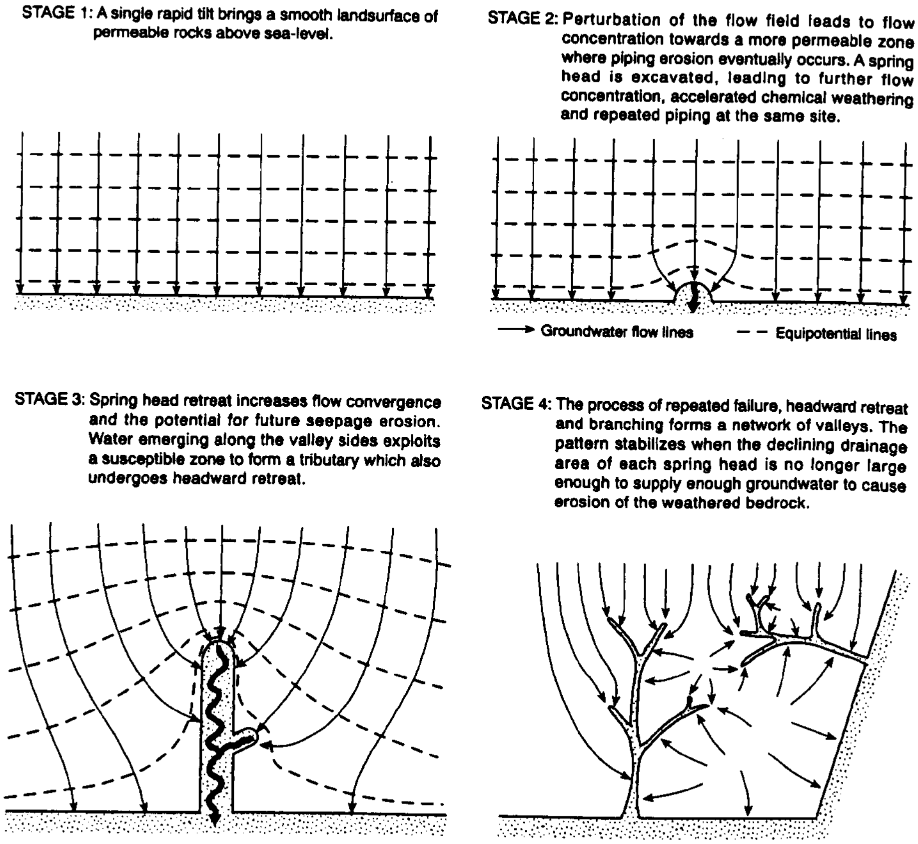


Figure 4.2 **A Model of drainage network development by seepage erosion (Dunne 1980)**

This also created problems, for unless the surface was deliberately tilted to 'enforce' a trend slope (which would have been inconsistent with the desire to model some particular region of the world), then the stream would inevitably encounter 'traps' from where it could not escape without running uphill. Sometimes a regional slope could not be used for the reasons outlined above, or because it was not part of the overall design for the area being modelled.

Clearly one of the key areas that must be tackled in any synthesised terrain model that depends on a geomorphological input is erosion. Erosion is the removal of rock, sand or any other material by natural agencies of water (rivers, the sea), rain (runoff), chemical disintegration, glaciation and so-on. Erosion is sometimes confused with weathering - the difference will be explained later on in this chapter. Essentially, however, any quality DEM or synthesised terrain set must take erosion into account if realistic (in any sense of the word) landforms and landscapes are to be simulated. This is because erosion is such an important agency in shaping the real world - it must therefore be accorded a correspondingly important position in the synthesis of landforms and landscapes generally.

This chapter is intended to explore the way erosion - primarily fluvial erosion - can be described, understood and harnessed to the needs of the synthesised terrain research PhD study programme. The other side of the coin to erosion, is, of course, deposition, since all the material removed must end up somewhere - there is a conservation of mass generally in the earth (apart from the accretion of a minor amount of stellar debris and meteorites).

Special problems can arise when considering erosion and deposition. These problems revolve around the detail to which modelling erosion and deposition should be pursued - this can be extraordinarily difficult even at a simple level. This chapter, therefore, identifies some related issues and outlines methods that exploit simulated fluvial erosion in connection with the synthesis of terrain at various scales. Deposition is also explored, but as an incidental subject. The software is also mentioned as further coding was required once the algorithms were established.

The approach taken in this chapter is as follows:

- Definition and description of Erosion 'types'
- Collection of common types and rejection of 'special cases'
- Modelling and simulation of fluvial erosion types (algorithms and approaches)
- Deposition (definition, modelling, effect on overall system etc.)
- Links to existing software and work already done
- Conclusion and summaries, with a recommendation.

4.3 Definition of Terms and Erosion Concepts

This chapter is concerned mostly with the simulation of drainage basins, with their attendant 'typical' landforms. Some observations on various aspects of erosion and deposition are made, some of which is followed up in the following chapters. Erosion is the wearing away of landforms by natural (and in rare cases artificial) processes. More precisely, it is the process by which the landscape (soil, rocks, river beds, cliffs, beaches etc.) is attacked by a variety of processes - usually climate-driven - so that pieces are removed and deposited elsewhere. This can be the washing away from a sand grain in a stream to the wholesale planing away of tons of solid rock by a continental ice sheet.

The term 'weathering' is sometimes encountered. Weathering is really a subset of erosion, in that it represents the micro-level disintegration of rock fabric (or other material) by means of the elements, so a combination of chemical and mechanical processes are at work. For the sake of continuity, weathering will be dismissed in this chapter and only erosion will be used, to avoid any semantic arguments or possible confusion. For example, deep weathering can give rise to the tors of Dartmoor, which are then exposed to erosion proper as well as weathering (Linton 1955), and although these are not strictly speaking fluvial landforms they tend to be found on summits, on interfluves and valley sides.

4.3.1 Models and types of Fluvial Erosion

Erosion - on a general level - is divided into *uniformitarianism* (or continuous processes) and *catastrophism* - both are concepts which have exercised the minds of earth scientists for many years (Huggett 1990). Continuous processes are described as the gradual wearing down of fields and hills over millennia, by rain, runoff etc. (Pitty 1982, Sumerfield 1991). Catastrophic processes are probably more significant in some cases, as this involves, for example, a large section of seacliff collapsing over a period of days or hours due to a severe storm. The catastrophic model assumes that sudden and possibly violent processes are at work, and this philosophy was adopted up to the 1880s - with events such as Noah's Flood used as 'evidence' (Knighton 1998). The work of Lyell, Playfair and Hutton (see Holmes 1972) undermined the catastrophic philosophy somewhat and introduced *uniformitarianism.*

Wolman and Miller (1960) asserted that events of reasonable magnitude and periodicity perform most of the 'work' done by rivers tends to agree with the uniformitarianism concept, and yet a more modern form of catastrophism has emerged in the late twentieth century (see Benito 1997). Indeed, catastrophism places an intellectual demand on any geomorphologist - landslides and large floods fall into this category and cannot be dismissed. As far as the river model is concerned, the two concepts were brought to the attention of the users and discussed. A 'happy medium' was found along the lines of the 'episodic model' as discussed for terrace development by Womack and Schumm (1977). Indeed, this happy medium can be extended, where, for example, Huggett (1990) discussed a unification of uniformitarianism *and* catatrophism via the field of non-linear dynamics - this union is called 'gradualism'. This argument takes the algorithm developer into Chaos theory (Phillips 1992) and in effect became too unwieldy for simple models of stream and drainage basin development as far as synthesised terrain is concerned.

This leads to the concept of equilibrium and dynamic equilibrium in streams, where in the case of the latter the dynamics of stream flow, erosion and deposition produce a kind of environmental stability (Knighton 1998). Again this is a difficult concept to apply in any simple or generic way, especially when the sponsors and users of the synthesised terrain programme of work were non-geomorphologists and had insisted on simplicity wherever possible. In consequence, these important concepts are not ignored, but they are deliberately either scaled down, simplified or simply not included in the algorithms. The important point is that they were considered, and that the user/sponsor (the ultimate arbiter of any refinement) felt that there was little to be gained by pursuing such detail. However, this still remains a subject for discussion and it is hoped that future work will examine these areas in more detail.

Drainage network composition and density are important topics for anyone attempting to produce a serious and geomorphologically-viable model of synthesised terrain involving river valley scenery. The systems of stream ordering and drainage density, as introduced by Horton (1945) and modified in 1952 by Strahler, are of paramount importance to synthesised terrain, as the synthesised rivers can be

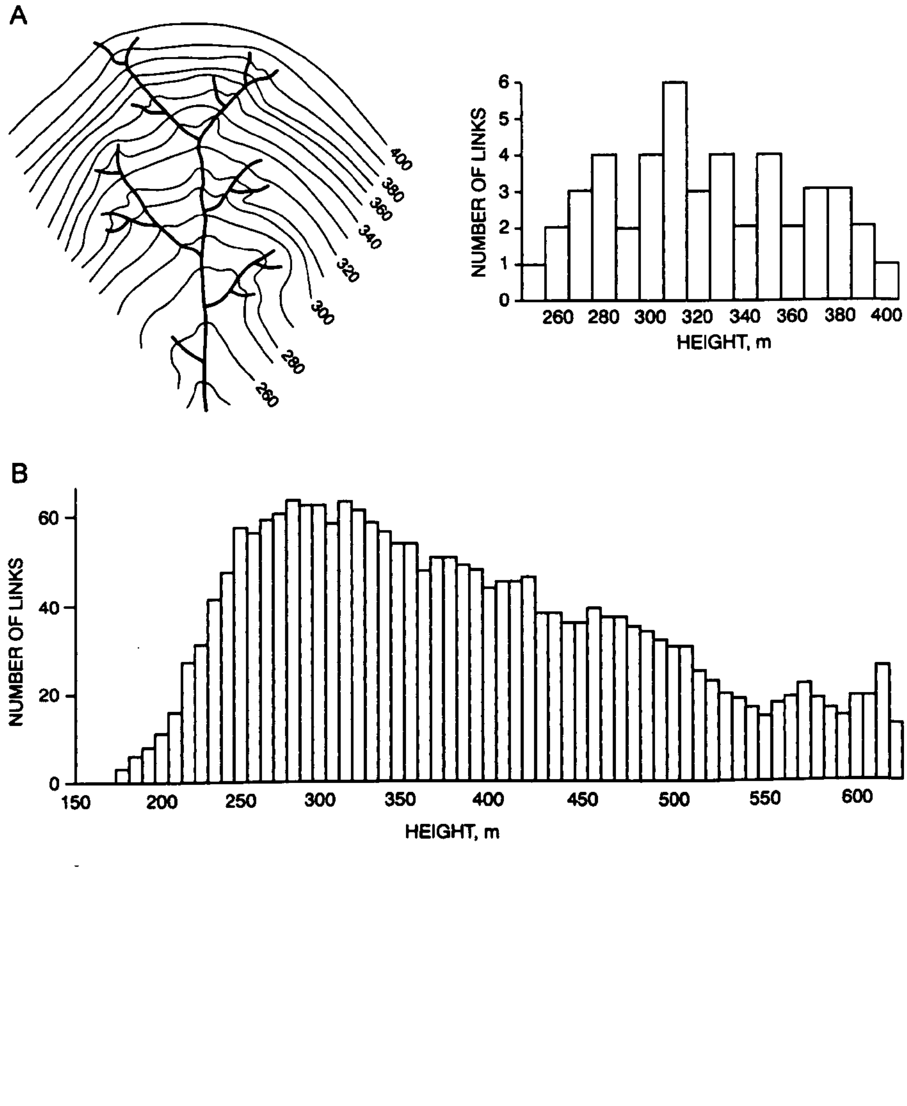


Figure 4.3 A - Derivation of the link concentration function B - Link concentration function for the River Noe, Derbyshire, England (magnitude = 287). After Knighton 1998.

'edited' to obey the principles of stream ordering: see also Strahler (1957, 1964). The basic model is as follows:

(a) Fingertip tributaries that originate at a source are designated *order 1*

(b) The junction of two streams of order u forms a downstream channel segment of order:

$$u + 1$$

(c) The junction of two steams of unequal order u and v, where v > u, creates a downstream segment having an order equal to that of the highest order stream

However, since rule (c) violates algebraic law and is out of accord with physical reality (Jarvis 1976), the system can be re-ordered by using channel links ordered by magnitude (As an example, figure 4.3 shows the derivation of the link concentration function based on the river Noe, Derbyshire, England. Schumm (1956) added another law, the law of drainage areas. Shreve (1966) and others built on the basic models to produce the 'laws' that can be summarised and applied (if only retrospectively) to synthesised fluvial terrain. This is most useful, as it found favour with the sponsors of the synthesised terrain projects, who naturally wished to keep realism balanced against the 'cost' of applying what they saw as 'esoteric and sometimes difficult' geomorphological models.

Erosion is another subject where it is difficult to find a 'cut-off point'. For this reason, raindrop impact is ignored as being far too detailed for inclusion in the model, even though literature does exist on this topic (Brandt and Thornes 1987). Equally, overland flow or sheetwash is assumed, just as one might argue that the rain itself is an assumption. Yet overland flow is regarded by Horton (1945) as an obvious starting point for channel initiation. Therefore the various types of fluvial erosion have been grouped together: channel size, bank erosion and so-on are largely disregarded, as the resolution of the DEMs is not sufficiently fine to take into account such features.

To overcome the problem of 'where to start' - the research concentrated on finding 'generalised' models. The work of Montgomery and Dietrich (1994) lists several types of erosion which contribute towards the initiation of channels, including overland flow, landslide erosion, seepage erosion and diffusive erosion. This again underlines the catastrophic nature of some geomorphological processes but is probably too detailed for the fluvial - and essential morphometric - models desired by the 'customer'. The scale of the DEMs tended to preclude modelling real overland flow and micro-rills, although it is acknowledged that these are of course important factors in the 'real world'.

As a result, the research turned to more helpful models of network evolution. While admitting that the topics mentioned are important, it was decided that lack of resources meant that only the most important factors could be included in the process model. The research therefore turned to network development. Some artificial or recently exposed networks have been created and or observed (Schumm 1956, Morisawa 1964) or recreated under laboratory conditions (Flint 1973, Parker 1977). Indeed, the monitoring of streams and their attributes, sometimes over many years, is a common and obvious theme in hydrology and fluvial geomorphology (Knighton 1998, Lane *et al* 1998).

Parker's (1977) work suggested that the networks grew by headward extension and bifurcation of first-order streams. Through inspection of topographic maps, Glock (1931) had already suggested that there are several patterns including *initiation, elongation, elaboration* (by the addition of tributaries), *maximum extension* and, finally, *abstraction* as streams are lost due to changes in relief over time. Horton's (1945) deterministic model is still regarded as a way that evolution can be 'rationalised' (see Griffith 1998), although other models by Dunne (1980, 1990) and Willgoose *et al* (1991a, b and c) have extended this original work, which, after all, had already been suggested (by Schumm 1956) to apply to small-scale networks with low vegetation cover, low infiltration capacity and limited soil cover. This last point could be an advantage as far a synthesis is concerned as many of the 'primitive' surfaces have been - or will be - be in this condition. Willgoose *et al* (1991a, b and c) attempted a simulation of network evolution (see Fig 4.4). This model is used for assessing thresholds (such as the conditions under which channels extend headward). This is a model for understanding geomorphological processes, not for synthesising terrain, although some of the concepts have been noted with interest and tested against ideas which make up the stream process algorithm. Indeed, the extensive research carried out into stream and river network form and process has been found to be invaluable for two reasons:

- it is intrinsically useful and adds to the knowledge base - and therefore the likely quality - of simulated rivers
- it is useful in the process of evaluating the synthesised drainage basins and fluvial terrain for validity.

4.3.2 Types of drainage basin

There are several types of recognised 'classic' drainage basins, and these have been in use for a long time, mainly to illustrate such topics in textbooks (see Small 1990). Way (1968) suggested eight types, ranging from the well-known radial, dendritic and trellised drainage patterns, to others (Figure 4.5), such as annular (where the runoff is

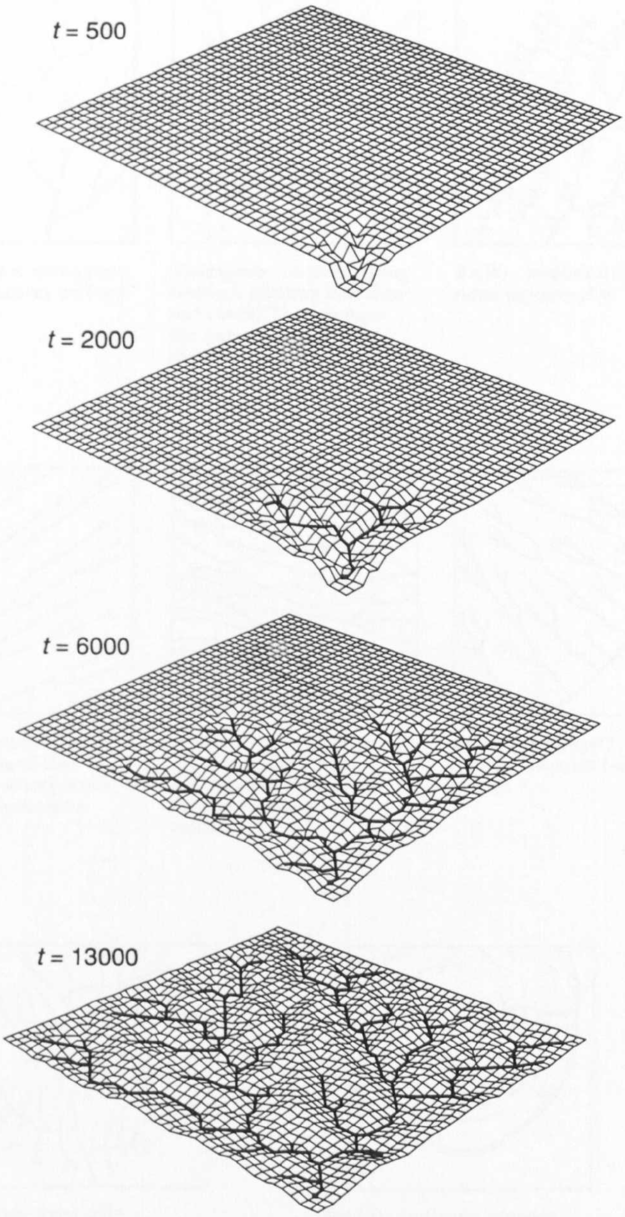
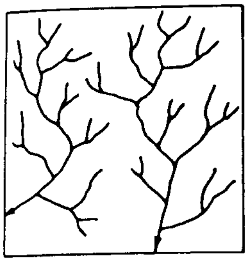
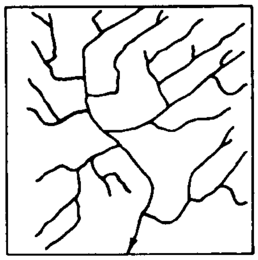


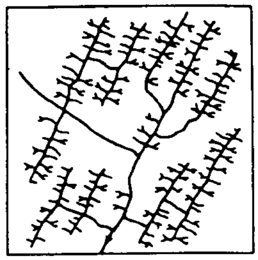
Figure 4.4 Sample simulation of network evolution (Willgoose et al 1991a and b). Times (t) are non-dimensional.



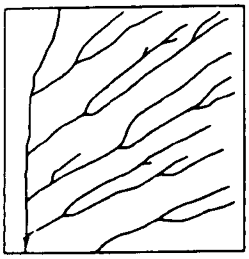
Dendritic: the commonest pattern. Indicates uniform materials.



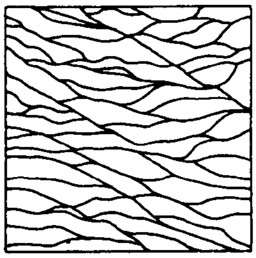
Rectangular: implies strong bedrock jointing and thin soil cover. The stronger the pattern, the thinner the soil.



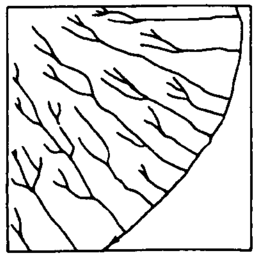
Trellis: implies strike ridge topography.



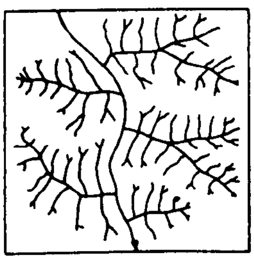
Parallel: characteristic of outwash areas of low topography, where main stream may indicate a fault.



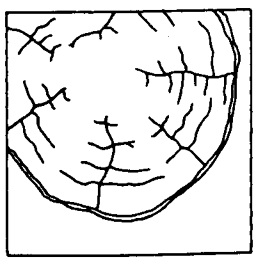
Anastomosing or braiding: in alluvial areas where sediment load exceeds carrying capacity of a stream.



Radial (centrifugal): in isolated circular hill masses.



Pinnate: generally indicates high silt content as in locss or on flood plains.



Annular: indicates igneous or sedimentary domes with concentric fractures or escarpments.

Figure 4.5 Types of integrated drainage patterns (after Way 1968 - the main six types only are shown).

influenced by an igneous dome with concentric fractures or escarpments) - indeed this model compares favourably with some of the figures produced in this thesis for mountainous and upland scenery (see chapters five and six). Chapter five shows several 2D and 3D pictures of some rounded upland landforms from an 'alternative North Africa' with - in general - a radial drainage pattern forming on them - and all based on completely synthesised terrain. One of these is shown in Figure 4.6, which demonstrates some test results of combining simulated drainage basins, and other examples are perhaps best viewed in the sequence of Figures in Chapters five and eight, indicating the watershed, contours, storm channels and permanent stream channels. Figure 4.6 shows green 'hills', with blue representing attempts at stream runoff. Features in red represent culture and are dealt with in Chapter 8. The figure was included to remind the reader that many hundreds of test runs were necessary before accurate or satisfactory results were obtained. In contrast, Figure 4.7 shows an intermediate attempt at producing fluvial synthesised terrain, where the river is marked manually, but a distinct floodplain can be discerned, dominated by high cliffs and hills (this was an early attempt based on an existing landscape and the parameters used have not been retained). However, it shows the ability of the algorithm to (a) create valleys (b) create a floodplain.

Floodplains are regarded as ubiquitous features (Griffith 1998), and in any case floodplains needed to be modelled as many key physiographic areas designated as AORs included impressive floodplain regions. If floodplains are regarded as areas where successive deposition (under exceptional discharge conditions) causes sedimentation which is successively augmented (Small 1990) then they clearly are important features simply because they grow - they do not 'go away'.

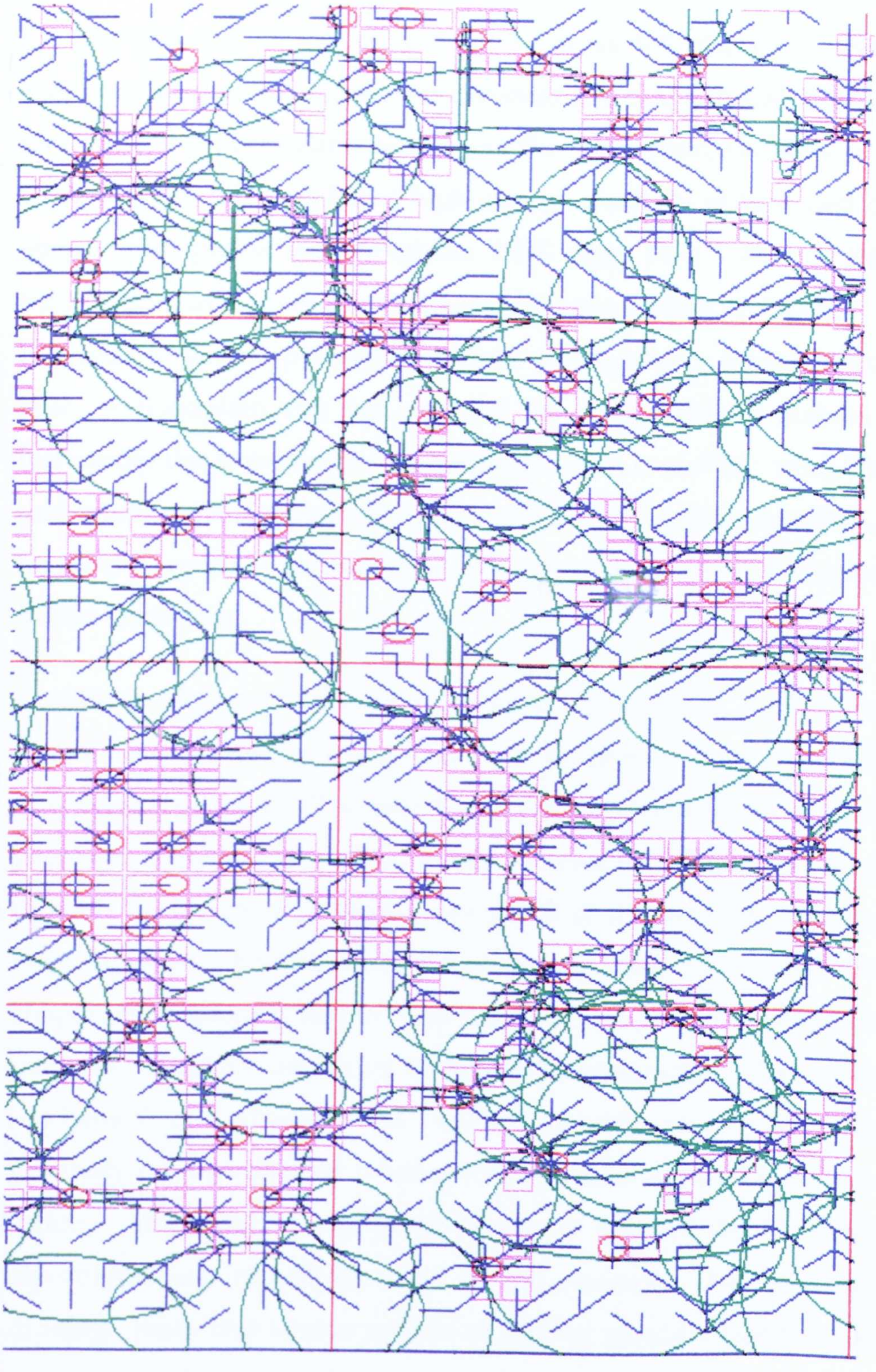


Figure 4.6 Test exercise using Geoforma.

Wolman and Leopold (1957) asserted that lateral accretion and ('within') channel deposition account for up to 90% of deposits and are therefore the dominant processes involved (see also Leopold *et al* 1964). One model of particular interest was the work done by Nanson and Croke (1992), who modelled high-energy, medium energy and low-energy floodplains (see Knighton 1998 page 147). This is useful information, as it gives the synthesised terrain creator an 'option' that is rooted in geomorphological process and academic documentation. Also, a floodplain can be regarded as a depositional feature, so technically this exercises the synthesised terrain modelling 'away' from just erosion, even though of course the real process is complex and involves a sophisticated relationship between erosional and deposition fluvial landforms.

Erosion is often a combination of processes - such as 'mechanical' - friction and shattering - and chemical processes - for example in a limestone area the $CaCO_3$ -based rock will be dissolved by the acidic agents in rainwater as well as being abraded by pebbles etc., so it is difficult to determine in some cases which of the two processes is the most effective. Fluvial erosion has already been mentioned in the chapter on methods (Chapter 3) as one of the list of simulated erosional methods. Fluvial erosion can, of course, be composite in that it can be mechanical and chemical (as outlined above), or drainage basins generally can be subjected to other forms of erosion apart from stream action. Modelling of composite forms is difficult in the kind of algorithm-based techniques used in the research. For example, a drainage basin that is also subject to intense glacial erosion or wind erosion would be a 'special case', and as such, complex. Composite or very sophisticated simulations, therefore, go beyond the bounds of the work, although it could be argued that the level of sophistication is already more than hitherto recorded for synthesised terrain maps. The types of possible erosion acting on a drainage basin are listed again, for

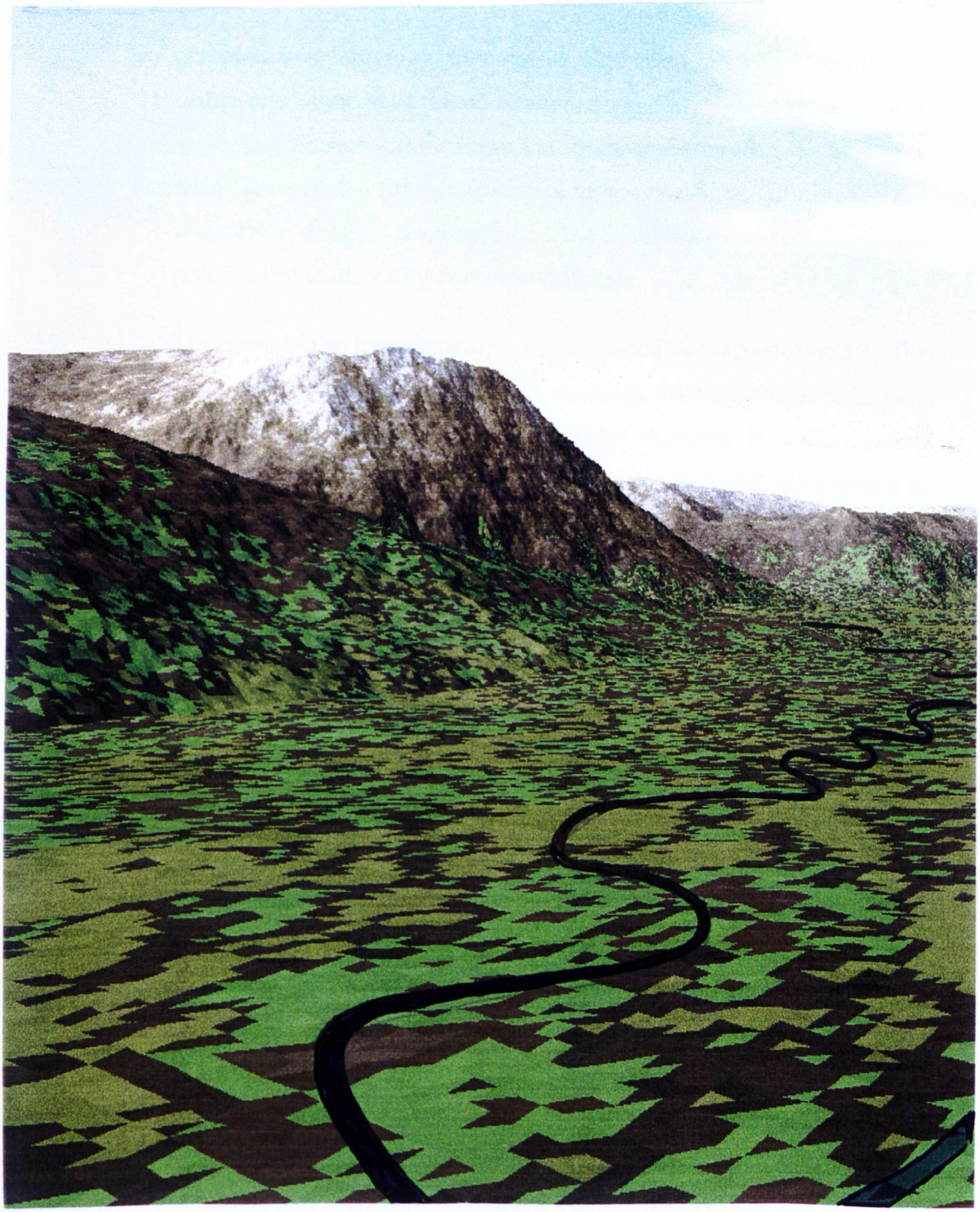


Figure 4.7 Early test exercise using Geoforma to create floodplain and high valleys (simulated course of river marked in manually).

completeness, although the stream algorithm does not specifically utilise any other than fluvial erosion along (however it is possible to apply any erosion algorithm to the drainage basin after the basin has been 'processed' - for example to simulate coastline. In practice this was rarely done as it complicated the synthesised terrain formation process and made validation most difficult).

Timescale is also important and was discussed in chapters 1 and 3. The absolute time factor in simulated drainage basin creation is largely irrelevant in this thesis (i.e. no attempt is made to assign actual timescales to processes) except that it 'moves forward' from event to event. This is mentioned when appropriate, or when other authors discuss such processes with respect to 'real-time'.

4.4 River Erosion and Runoff

4.4.1 Earlier Work

In a paper published in 1987, The author postulated a 'constrained random walk' process, which would model the path of several streams down a tilted 'trend surface' and which would form the pattern of the drainage basin. formations. The land was then etched out to create the river valleys, using the stream position (effectively the centre of the channel) as the lowest point. This paper is described again because it is a relatively early attempt to produce synthesised terrain or DTMs with geomorphological justification (following a careful reading of selected literature there are of course others, notably Carson and Kirkby (1977), Turner (1992), Ahnert (1987), Kirkby (1988), Evans and Cox (1999) and additional authors; also see section 4.5 in this thesis).

The landscapes created (with some modifications), when printed out as 3D perspective views, were surprisingly realistic, especially as a small random 'noise' function displaced every height by -1 to 0 to +1 metres in order to provide a surface roughness or variation. The conceptual problems were many - first a conveniently tilted surface was required, with simple geological structures (virtually zones on the map that weighted the river against 'harder' lithologies so that it tended to avoid the harder rocks). Also, the streams were always moving downslope, they never had to enter dead-ends nor were they forced to break-through barriers, since the primitive surface was invariably flat and featureless.

The most valuable driving force of the algorithm, and the one that contributed most to this thesis, is actually twofold; first there is the concept of etching out valleys regardless of the relative heights of the initial surface, and second there is the concept of 'forcing' a stream along a pre-destined direction but not a pre-destined path. Thus the stream channel can be the template against which a valley system can be etched: it is in effect the apex of an inverted triangle, the sides of which are the slopes and the base of which is simply a imaginary line from the top of one interfluve (or watershed ridge) to the other. If the valley is wide enough (say more than 1 km) then river bluffs and flood plains may be created during this etching process. The etching - really simulated 'single-shot' erosion - can cater for any type of slope, and can take into account geological or relief features. Relatively realistic appearing river valleys can be created this way (see the diagrams in chapters 5, 6 and 8).

4.4.2 Research Requirements

For prepared surfaces such as those created by terrain classification and evaluation methods, the problem is more acute, as the primitive surface is made up of terrain derived from a process which 'typifies' an area of the world. The simple, conveniently tilted flat slope is therefore unlikely to be present, and the streams may find themselves running into lakes or impossible situations such as 'dead ends' where all options lead uphill. However, there are solutions to such problems.

Several general solutions were considered by the author. For example, all surfaces could be made to have a regional 'slope', even if this is contrived, by tilting the primitive surface. Without it, the concept of 'stream walking' is difficult although not impossible. However, apart from somewhat negating the whole point of the parametric analysis, even tilting primitive surfaces did not necessarily get rid of 'dead ends'. Secondly, the author had already invoked the technical theories and papers on river dynamics, valley and stream morphology and hydrology and realised that there are rules (or at least principles) that govern such topics. For example, there are limits to the numbers of streams 'allowed' in a catchment area (drainage basin). This means that streams created 'on the fly' may need to be removed if they do not comply with classic theory (see for example Shreve (1966)). Indeed, Figure 4.8 shows an 'imaginary' drainage basin showing Strahler's stream ordering system (see Chow (1964) and Horton (1945) for background). Horton's work has in its turn stimulated further work, such as that of Haggett and Chorley (1969).

One advantage of a drainage basin as a unit with 'laws' is that 'problem' streams can be removed - in other words if five streams of a certain order are expected, but one flows into a dead end, then this stream can be temporary abandoned and another stream can be tried. If this stream successfully reaches another stream (to become a tributary), or if it reaches the edge of the AOR, then the 'problem stream' may be removed in order to make the simulated drainage basin fit the principles of 'Hortonian' concepts and the 'Shreve count' in a successful way.

The assumptions for the 'river walk' algorithm are as follows:

- The river should flow downslope in a general sense.
- A regional slope should be defined to aid this

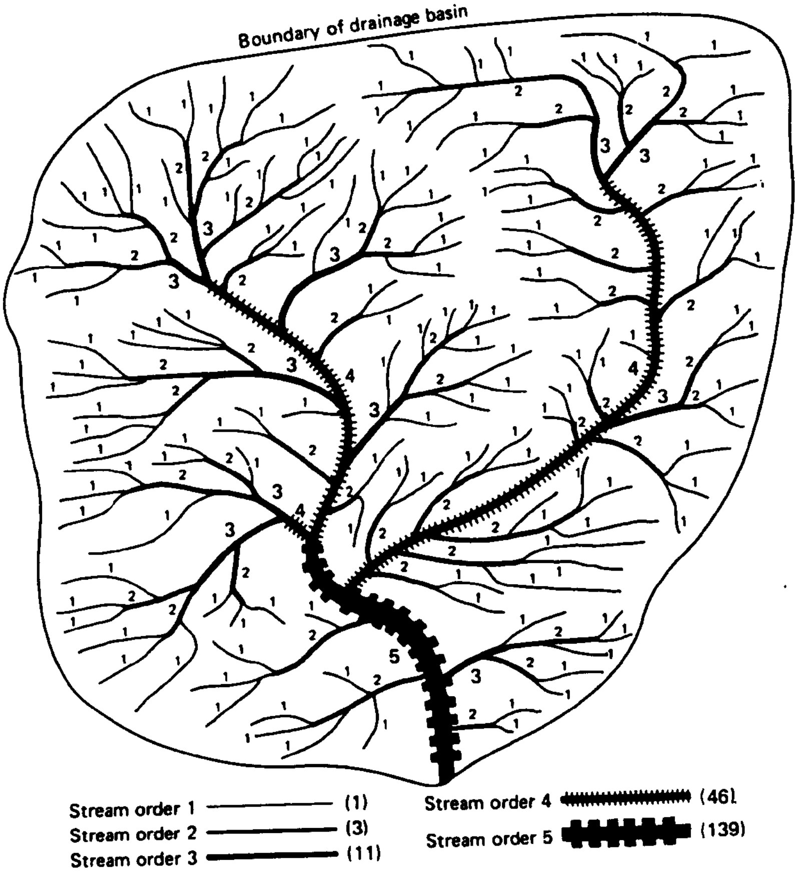


Figure 4.8 Imaginary drainage basin showing Strahler's stream ordering system (after Mitchell 1991).

A matrix of points (pixels or x,y,z Cartesian system should be used - not vectors, strings, irregular points or any other system unless this has been agreed and justified.

- A stream must not wander uphill

If a stream wanders into a 'dead end' it can be adjusted by post-processing to take one of the following actions:

a) The stream 'stops' as if it disappears into a pothole (this can happen in limestone areas).

b) The stream can be removed later following a 'Shrevian approach', to coin a phrase.

c) A lake can be formed, with a 'break-out point' scooped out by 'later erosion' - e.g. When the valley slopes are created. The boundaries of the lake can be fixed to a contour either automatically or manually. If a 'lake frequency constant' approach is being used - e.g. some factor that tells the operator if the AOR should be naturally populated with lakes - then this can be invoked. The author has observed, by field inspection, the 'break-out' point of the river Glomma from Lake Oyern in Southern Norway (near Askim): downstream the Glomma runs through gorges yet for the largest river in Norway it has no appreciable river valley, so recent has been the establishment of the drainage system since the end of the last glaciation.

d) The stream can continue by removal of the obstacles prior to the 'valley scooping' phase.

e) If a convenient lake or coastline is nearby then the stream can be directed towards that feature.

Other points to be noted are as follows:

- The valleys should widen proportionally as they are traced downstream (see Richards 1980)

- The long profile of the stream must approximate natural observations (e.g. it should ideally match text-book profiles and take account of nick-points etc.).

- A meandering algorithm can be based on any interpolation routine that produces appropriate bends - a tested method was based on a sine-wave with an exaggerated loop. There are many academic observations on this topic but it is recommended that meandering should only be 'allowed' if the terrain classification AOR allows it, and/or if the stream is in its 'mature phase'. Oxbow lakes and extreme meandering should not be attempted unless specifically requested by the user as such features have proved difficult to model without manual intervention, since the river has to be redirected and the cut-off indicated in the DTM as a lake form.

One interesting suggestion is the use of post-processing concepts. This means that some adjustment can take place after the creation of the primary surface in order to make it 'stream-friendly'. This means adjusting the DEM slightly, manually if necessary, so that streams will NOT encounter difficulties such as dead-ends during their 'walks'. This suggestion carries considerable merit - based of the alternative of 'cure' instead of 'prevention' - and was included as 'IF' conditions (logical conditional programming using the classic 'IF-THEN-ELSE' block) in the stream programs. Any manual adjustment may need to take into account the 'viability' or geomorphological sensibility of the terrain - in other words, any adjustment should not damage the basic integrity of the terrain. The criteria by which such damage is inferred (or not) is difficult to judge, and forms one of the philosophical issues examined in chapter nine in this thesis.

Finally, some of the existing work on the 'cul-de-sac' problem was examined. The D-8 method of Fairchild and Leymarie (1991) - which is a simple routing model for streams - can be adjusted to take account of depressions by assuming that such areas are 'spurious' (Freeman 1991) and systematically elevating all the cells in the depression to the level of the lowest outlet, thereby making a flat surface (Jenson and Domingue 1988, Martz and Garbrecht 1992). Garbrecht and Martz (1996) presented several automated DEM data extraction procedures in their paper, although some of the examples were referred to real catchment areas. Garbrecht and Martz also discussed automated landscape parameterization procedures for raster generated drainage networks. These methods were considered, and could have been built into the model. However it was found that the current system (or algorithm) was satisfactory, even though it is important to be aware of alternative methods should the need arise.

4.5 Erosion of valleys and sequence of events (simplified)

In real life, the fluvial erosion of valleys, sometimes involving the removal of material down to thousands of metres, could be offset by the land rising due to isostatic recovery. Therefore the rivers will 'eat' into a landscape that is slowly being raised above sea level. This concept of mountains being raised thousands of metres is an entirely usual process and is not 'invented' as a special case for the synthesised terrain work. This is currently happening over most of Northern Europe, and is suggested as a convenient method of allowing the primitive surface to be gouged out and simultaneously lifted without the streams digging themselves below sea level.

In this way not only realistic valleys (with S-shaped, V-shaped, concave, convex or any other shape according to user selection), but also interfluves, flood plains, river bluffs and other features can be created. For example, a river bluff can be a gentle, low cliff parallel to the valley side x metres from the channel and y metres from the valley limit, or watershed boundary. In general terms a river can meander on a 'trigger' basis - if a certain percentage of flat or relatively horizontal ground is encountered this can be interpreted as a flood plain.

Slopes and their interrelationships with other landforms have been examined in the literature, referring particularly to worker such as Ahnert (1977, 1987), Kirkby (1969, 1988), Evans and Cox (1999) and many others. The morphological and mathematical aspects of slopes have already been discussed in chapters two and three respectively, and there is more relevance for this work in a general sense to acquire the form of a slope, rather than to simulate the slope process. This is not to overlook process, it is simple a pragmatic decision made in the face of too much possible information for algorithms that are already tending towards over-complexity. However, slope are important, and deserve somewhat more treatment than they have received above. As a result, hillslope hydrology is examined briefly later in this chapter.

The sequence of river creation is discussed later on in this chapter. Lakes can be emplaced later by manual methods or they can be created 'automatically' from an application of the original 'dead-end' river paradox (where a simulated river has no 'downslope' direction in which to flow and it is 'obliged' to create a lake by the simulated filling of the depression in which it occupies. An alternative method is to deliberately simulate the flooding of the area then allow the river to continue once low ground is perceived once more. An outlet channel can then be defined if the river is to continue on its way (see Freeman 1991).

4.5.1 Settlements and man-made effects

Settlements or other man-made effects are not mentioned in this chapter, nor are any other types of special man-made activities, such as the building of dams or dredging. Even more subtle man-made effects can change the nature of streams: a feature such as a small river terrace could be created by subtle adjustments to the simulated channel under certain conditions: Knighton (1998) describes a real example of a terrace on the Ringarooma river in Tasmania, where mining detritus and the exposure of previously buried tree stumps has created a terrace on one of the banks (see Knighton 1998, page 328).

This apparent disregard for the minor and major effects of man is deliberate, indeed the processes considered in this chapter are entirely natural and themselves are far in excess of what could be realistically synthesised - one is tempted to state that this entire thesis could be based on the synthesis of fluvial geomorphology; taking into account geology, climate and hydrology - such is the level of potential detail. However it is worth repeating that a line must be drawn even as far as the natural effects are concerned, and since Man has also had an effect on stream erosion and deposition by various activities - this level of modelling is beyond the scope of the work. Having stated this, some man-made effects are considered in a general sense - mostly based on deterministic or user-defined actions - and are covered in chapter 8 which deals with man-made DTM features and 'culture' or 'infrastructure'. Man-made effects are mentioned briefly for completeness, and include:

- Deforestation (which can drastically affect the discharge (Q) amounts and precipitation-runoff delay times, among other effects).
- Extraction of water from substrate to alter water-table
- Bridges, dams and other obstacles, which can change river characteristics

- Direct alteration of stream channels by engineering projects (e.g. straightening out bends or canalisation of rivers such as stretches of the River Cherwell in Oxfordshire, England)
- Indirect effects such as increasing urbanisation changing catchment areas and therefore affecting the rapidity of overland flow; changing the water table by artesian well extraction, etc.
- Direct effects such as damming rivers, Hydroelectric power stations, etc.
- Mining and extraction industry 'damage'

Indeed, some streams exist today only as underground drains, and have disappeared from the surface map altogether. For example, the River Fleet, which drains southwards into the Thames in London, is completely routed through tunnels and has no surface exposure, yet it was a considerable watercourse in the days of William Hogarth, the famous English artist and cartoonist who lived in London during the early 18th century (Uglow 1997).

4.6 The proposed algorithms matched to the research software

4.6.1 The fluvial erosion problem

Over the course of the project many topics of research and development have been examined. Indeed, it is the maxim of any 'true' research project that, to some extent, there is the luxury to expend effort even if it leads down a 'dead end', as it could equally yield rich rewards. Similarly, the elimination of spurious effects or the uncovering of 'negative evidence' - although apparently unrewarding - is also information in its own right. Not all research themes lead triumphantly to a successful outcome - otherwise by definition it is not research. The current research project started the modelling of drainage basins on the basis of assuming that simple erosion - mainly fluvial erosion - could produce most of the landscapes required. This was because of the current thinking of the author, as expressed in papers such as Griffin (1987), where stream erosion was made to create realistic-looking valleys and relief, with some stochastic and geological influence.

It was soon apparent that this was not enough - first a method had to be devised to represent areas of the world on a 'dial-up method' - and this turned out to be based on terrain classification. However, this by itself was not enough to produce the realism - so the pendulum swung back towards erosion methods again. Indeed, the conclusions were being drawn that a mix of the various methods would be necessary, depending on circumstances. This was one of the most profound realisations of the PhD research project to-date, and leads to the way towards the 'ultra-realistic' terrain being produced by the software module Geoforma and its derivatives.

The significant difference is that this time the erosion is being carried out on a primitive surface that already is representative of a part of the world, instead of a flat horizontal plane. The combination of terrain classification, fractalisation and erosion (process-response models) all add up to give the research work its end-product terrain the realism it requires not just for use by the 'end user' or sponsor but for the satisfaction of creating such landscapes in a geomorphological context. This part of the chapter is concerned with the final 'polishing' by simulated erosional processes which give the geomorphological viability yet retain the geographical attributes and appearances.

4.6 The software: Geoforma

The Geoforma software has already been described as highly interactive programs using a 'form' or GUI window to select options, or that can run a software tool or device called a project 'wizard' to create a new landscape file for a special purpose (e.g. a new set of terrain outputs). Therefore all the components will cumulatively create the overall simulated map. An Area of Responsibility (AOR) can be created from a new region by means of a map sheet, or (and this has been of particular interest to DERA and other organisations using NATO standards) the user can load in DTED and DFAD format data. This chapter is, of course, concerned with the fluvial aspects of the physical landscape - but it is important to emphasise that the software is highly integrated and other topographic features may be combined to form a DEM. Moreover, the original version of Geoforma (called *Geomix* and subsequently *Geoform*) was developed specifically for drainage networks, slopes, valleys and interfluves, and no other features, by the author (Griffin 1987).

4.6.1 Manual Control

Part of the software allows the user to invoke the terrain topology component (macro-relief) - known as control surfaces - which can be moved around or otherwise manipulated manually.

A user can also define a *trend surface* - which is a generalised plateau or area of terrain. (A real example might be the slopes leading from the tors of Dartmoor in Devon, UK, down to the edge of the moor where the countryside changes from planar granite with outcrops of rock to more undulating farmland). As mentioned earlier, fractals have already been used to simulate 'real-world' rivers (Le Barbera and Rosso 1989, Tarboton *et al* 1988 and Rinaldo *et al* 1992,) although Knighton (1998) - citing Philips (1993) - suggests that attempts to correlate the length-area relationship with Horton's ratios (bifurcation and stream length ratios) have not been 'entirely convincing'.

The software allows the user additionally to change convexity and concavity of features by altering slope coefficients. These points are important, as although concave features or 'holes' are imprecise descriptions of landforms, the general concept of negativity is useful for simulated valley manipulation, as slopes will have to be 'gouged' from the primitive and the slopes of river valleys can be V- or U-shaped, or tend toward concavity or convexity, depending on the circumstances.

4.7 Drainage

At present Geoforma builds a flow direction map - represented by groups of arrows - and also shows 'pits' and (indirectly) watersheds as features on the map. These are matrix based. The user can select 'run stream network' and the resultant display will be a series of squares. The interpretation of these is that hollow red squares are possible launching points - as these are always at the springhead (the technical term for the source of any stream or river). Solid areas on the display shows where the software has 'launched' a stream. Springhead and catchment areas are perfectly ordinary and acceptable stream features and would be expected to be found on any topographic map where fluvial activity has taken place. What is now needed is a way of enforcing erosion based on the positional data yielded from the software.

4.7.1 Editing: Methods of overcoming the 'dead-end' paradox

The 'dead end' paradox is where a simulated stream running through a primitive surface may find itself in a cul-de-sac. Other workers have hit this problem and some discussion has been reported earlier in this chapter regarding the different ways it could be resolved. However, not all of the academic work was available at the time the dead-end (or cul-de-sac) problem was encountered by the author, and so three methods were evaluated and tested. These essentially are methods of 'editing' the DTM. With the benefit of hindsight it may have been easier to reduce terrain elevation 'cells', although this may also (in some cases) compromise the integrity of the surface over which the stream is travelling.

(a) **Method One:** The first suggestion is to allow a random constrained walk, with meander tendencies (see Griffin 1987), in the direction of regional slope. This will place the stream in a generally downhill direction but it may run into problems if it reaches a position where all surrounding points (or 'cells') are above it topographically speaking (since it is programmed to run downhill). This means that the stream has run into a 'dead end'. There are several ways that this can be overcome.

First, using catchment delineation data and scanning downslope the stream can be 'forced' up over an obstacle, such as a ridge blocking its path. This is acceptable but only if the ridge is a minor feature. For major features the stream may need to be 'stopped' and used later in a stream capture algorithm. Stream capture is a real geomorphological process which is well documented (see Wooldridge and Linton 1955, Howard 1971), where 'back-sapping' (the wearing back of a valley) eventually causes the 'capture' of an adjacent stream or river by breaking through into its valley. The valley left by the captured stream is known as a 'dry valley' (although these can also occur due to other reasons, such as water table effects). If other streams are then run successfully down the regional slope without running into box canyons or dead ends then several options are possible:

- Using the works of Shreve and other authors the stream may be removed to correct the stream to area/catchment ratio (which in effect makes other methods redundant)

- The 'problem' stream could be assigned a continuous contour into which it flows, thereby creating a lake. This means scanning for a continuous enclosed area at the point where the stream 'gets into trouble'

- The ridge or obstacle can be removed by 'major surgery' or editing, as suggested in method Two (see below) - which can entail automatic or manual adjustment.

(b) Method Two: In this case, consider an AOR where 5 streams have successfully wound their way down the regional slope, with marginal obstacle-breaching. A stream remains 'stopped' at a depression, but has been continued as if the obstacle (let us say it is a major topographic feature) was not there. The method that can be used is similar to that used successfully by the author, where the channel of the steam (the exact point that the stream occupies) is taken as the centre of an interpolated quadratic curve, which effectively erodes the mass of material on either side without raising the stream channel height significantly (or indeed, at all).

How is this done? Several possible activities for coding are suggested:

First, simply by sweeping along an axis at right angles to the stream (probably a line running east-west if the regional slope is south or north) and replacing the landscape with a river valley. There is actually a geomorphic precedent for this, as uplift is continually being balanced by stream erosion in real life. This means that as mountain ranges and their foothills are uplifted by major tectonic movements, the streams are striving to achieve base-level and will erode correspondingly large areas in order to do this. Steeper slope and high precipitation (as on mountainous areas) will give the streams the cutting power to do this. The simulated valleys can be made more shallow and wider as the cutting process (the inverted quadratic fit) moves downstream, in order to simulate the stream becoming larger as more tributaries reach it (this depends on the scale being used).

Therefore the removal of such obstacles is perfectly in keeping with tectonic theory - it only remains to ensure the following:

- The AOR still resembles the dial-up original landscape
- The long profile of the stream is acceptable (in terms of current thought)
- Stochastic or fractal noise can be emplaced to avoid artificial-looking slopes
- The slopes themselves are adjusted for V-shaped valleys, or concave or convex slopes. These may be refinements if the coding becomes a significant piece of work.

  An alternative method might be to leave the 'trapped' stream until the drainage network has been established. Then, several different 'paths' can be made to extend the river from its stalled position to meet up with a river which is regionally downslope. This could be at a pre-determined point or where the random walk takes it. Each path could then be compared by assessing how much the stream has had to climb in order to reach its goal. This can be done by stepping through each channel point along the long-profile. The solution is the path of least resistance, which is equivalent to the minimum climb (and therefore the least amount of material that has to be 'removed' to create the channel). Simple arithmetic methods can be used to work out the path of least resistance.

Possible drawbacks are as follows:

- Removing the river in the event of no feasible paths needs care if other streams are dependent upon it

- There might not be any 'path of least resistance', in which case the program run can be repeated, with some modification of the vast obstruction blocking the stream.

- In rare cases a 'cross-roads' effect might be created, where the junction of a trapped river can be itself a tributary of another dependent stream (in other words some manual editing can rearrange the stream dependency to resolve the problem).

(c) Method Three:

The third method is to 'move' the stream manually, by means of an editing routine, to either capture another stream or to be captured by it (in other words, one becomes the tributary of the other). Some manual adjustment of the relief may need to be made in order to allow the rivers to flow in order to meet. This has the advantage of retaining the original features, although a warning message or a permission statement should probably be issued to the user. Again, this is following geomorphic theory and stream-capture is a common process.

4.7.2 Stream removal

One method of 'removing' streams which find themselves in particularly difficult cul-de-sacs is to invoke work largely started by Horton (1945) and followed empirically and experimentally by a host of authors (Strahler (1952), Schumm (1956), Hack (1957)). This involves 'growing' some tributaries, or even creating extra tributaries, so that the 'rogue' stream can be removed altogether in order to 'fit' the 'laws' of stream numbers and lengths (Horton 1945) and drainage areas (Schumm 1956). This is admittedly a 'rationalisation' but it appears to work, and it is another method of solving the 'sink-hole', cul-de-sac or 'dead-end' problem, depending on which author is involved.

4.8 General Erosion and Deposition

4.8.1 Introduction

Assuming that there are now potential solutions to dead-ends or difficult topographic features, the general problem of erosion needs to be considered.

4.8.2 General erosion using quadratics etc.

The method of sweeping at right angles to each stream (described above) is quite sound, as this is effectively what happens in nature. The method involves creating a series of linked quadratic curves with the stream channel as the centrepoint. The arguments for and against this have already been expounded (see above) although it has produced realistic terrain in the past when random 'noise' was also added. When the simulated stream channel is associated with a prepared surface (i.e. one that has been 'processed through parametric or other methods) the realism always appears to be better, although this has not been measured objectively.

4.8.3 Templates of valley profiles (as objects)

Another method would be to have a series of river valley/river floor templates, and apply these to the AOR. These templates would be stored as a series of 'look-up' profiles, perhaps indexed to some characteristic of the stream (such as gradient or length). They would be yielded by the original classification so they would fit the AOR.

Several hundred could be produced and chosen manually (in sets and subsets) or randomly - naturally they would obey the object-oriented approach of inheritance, sets and subsets, and other features. A typical template (actually a profile that is imposed with the stream channel as the centre of gravity) would be a flood plain, with two or three series of bluffs, with a valley side a certain distance from the channel.

It should be pointed out that a complex S-shaped valley side with bluffs, a flood-plain and an asymmetric profile would be extremely difficult to model generically by mathematical functions, even if simple quadratics and cubic curves can be used for 'simple' cross sections. Indeed, many man-years of research has gone into slope profile characteristics (e.g. see Ahnert 1987, Kirkby 1969, 1988) and this has been considered where possible. Mostly, a simple model was required because together the various components made the algorithms almost too complicated. This meant sometimes sacrificing an amendment to the algorithm, particularly with regards to the detailed control of slopes within the simulated valley.

The actual dimensions could be adjusted manually or automatically, so small streams would have small valleys and large streams would have larger valleys with perhaps an assemblage of terraces and bluffs. The beauty of this method is that stochastic or fractal noise can be applied to it at a micro-scale, and that it fits the original source area. Also, it implies both deposition and erosion, since a flood plain is a built-up flat area caused by aeons of flooding (high discharge or Q-factors combined with sediment dropping). This is an attractive method, therefore, and can be used together with, or instead of, the giant scale tectonic erosional sweeps described above.

4.8.4 Geology: a problem area

There are several ways of 'dealing' with the synthesis of geological structures or different hardness of lithologies. First, the geology can be set up by delimiting 'hard' or 'soft' rocks relative to the DEM and weight the simulated river flow away from the harder lithologies (as is done in Griffin 1987). This has the advantage that although it is simple, it can be set up relatively quickly to satisfy a user demand for an AOR. Second, the geology can be 'rationalised' after the event, in that the resultant simulated DTM can be 'mapped' onto a geological model that appears to 'fit' the topography. This was felt to be undesirable but it is still an option. Lastly, the geology can be omitted altogether on the basis that generic models are too complex. After all, there are case of 'inverted relief' where anticlines - and not synclines - support drainage systems (Holmes 1978, Renton 1994). Also, it is possible for a stream to exploit a fault in a relatively hard lithology at the expense of neighbouring softer rocks. Of these three options, only the first (and, on rare occasions, the second) were ever used.

4.8.5 Other Methods

A paper by Kelley *et al* (1988) should also be considered as this looks at a river valley/catchment area, with all the streams and tributaries etc., as a 'surface under tension'. This is interesting and some ideas could find their way into algorithms and eventual coding in Geoforma. However, the paper only really demonstrates a model to create images for flight simulations etc., and is therefore involved with approximating catchment areas instead of taking the difficult approach (as is done in synthesised terrain research) of basing process-response models on real areas of the world. There is no attempt at terrain classification, therefore, and the results are based on 'realistic-looking' images - this brings us back to the apparent realism of fractals used by non Earth-Scientists. To be fair, the paper is in the field of computer graphics imaging, and would not be expected to deal with the sorts of problems faced by synthesised terrain research workers. However, it is a point of view and as such needs to be mentioned.

Indeed, a diagram of the precipitation unit (see Figure 4.9) giving stream discharge Q at basin outlet lists - in a schematic way - all the possible types of positive and negative contributions to Q (diagram after Knighton 1998).

4.9 Conclusion of chapter

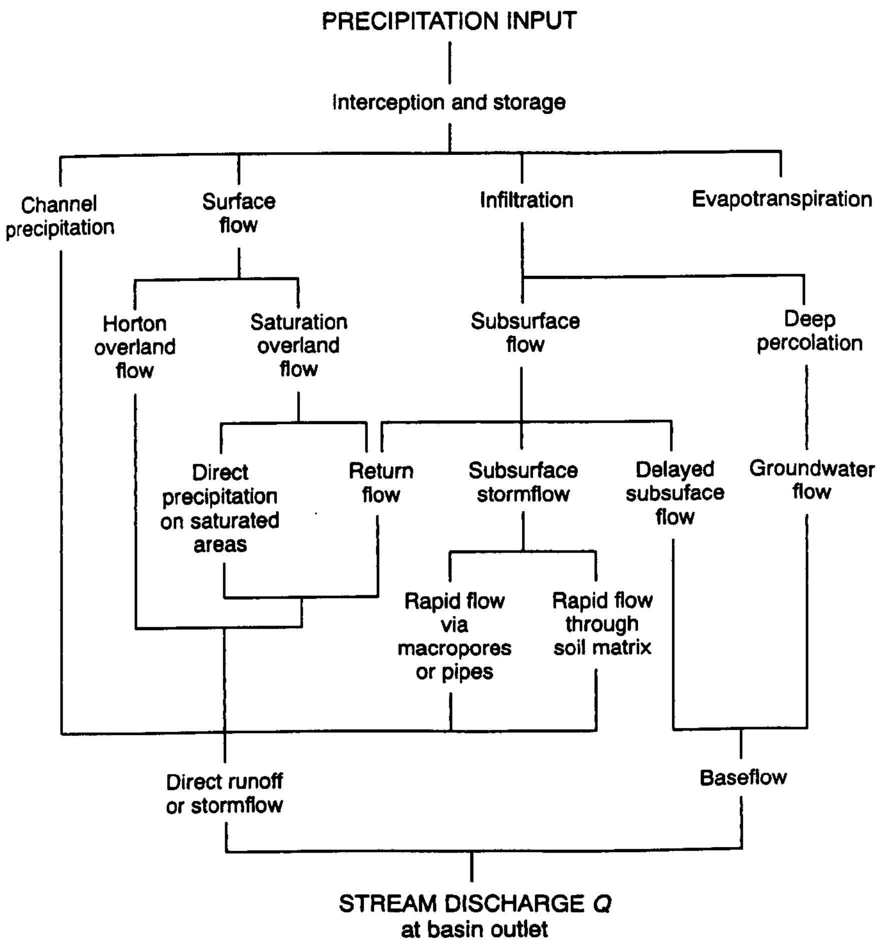


Figure 4.9 Schematic diagram of the runoff process (after Knighton 1998).

4.9.1 Summary of problem discussed

The problems facing the creation of synthesised terrain via fluvial erosion and deposition have been discussed and, in some cases, justified, in this chapter. Indeed the whole genre of applying computers and 'geostatistics' to terrain modelling is becoming increasingly fashionable (see Isaaks and Srivastava (1989), for example) and more literature is appearing that reconciles what used to be called the 'Quantitative Revolution' (when statistics were first used to support Earth Science theories in the 1960s and 1970s) with both traditional (e.g. classic geomorphology) and new methods - especially literature involving fractals and Brownian concepts.

Returning to the synthesised terrain research project, the problems that needed to be overcome by the author as the leader and algorithm developer of the Geoforma coding team were as follows (this list represents a functional catalogue of Geoforma):

- To continue improving and developing Geoforma and the derivative software, according to OOD (Object-Oriented Design), OO (Object-Oriented) programming and standards of quality and excellence.

- To understand and remind the author and co-workers that the synthesised terrain research programme has had user-requirements, along with requirements for specific scales, map types etc., and that this was driving the work, not academic interest alone. This was not a problem, but it is easy to become side-tracked in such a multi-disciplined subject area.

- To understand the basic tenets of erosion, deposition, stream dynamics and terminology, and how far 'super-realism' can or needs to go to provide 'customer satisfaction' (e.g. to create the surfaces and AORs that are needed and are of use to a sponsor). The term 'super-realism' is perhaps somewhat arrogant in itself, but the almost total lack of geomorphological validation by other authors attempting to synthesise terrain , except in those where there is a link with an area in the real world, suggests that this research is truly breaking new ground.

- To create erosion and deposition without spoiling the original 'dial-up AOR' concept
- To work at the best scale and with the right amount of stochastic/fractal effects
- To avoid manual intervention, if possible, that might defeat the object of producing autonomous patches of terrain
- To create river systems that 'make sense' in terms of their long profile, various accepted ratios (e.g. area to number of streams, number of tributaries etc.) and their path down a regional slope
- To choose various methods to avoid or avert the 'dead-end' river problem, by one of several methods (creating a lake, major 'obstacle-busting', river capture, removal of river according to 'Hortonian' and other principles or manual adjustment of local terrain).
- If chosen, create major erosion on the slopes modelled at right angles to the river axis, using an uplift/base-level tectonics approach to justify quadratic valley profiles or other methods for the 'scooping out' of valleys
- Using a set and subsets of cross-profiles as 'templates' - these are derived from the original area and can be used in a variety of ways. This effectively enforces both erosion and deposition and seems a

very attractive method. It may be used with other methods described above if time permits.

All these methods were examined and encoded, although some were left at a 'trial' status or not attempted (like invoking tectonics) due to the difficulties of finding 'generic' models, as geology is also hard to model on a general basis and was beyond the resources of the author apart from the consideration of simple algorithms).

4.9.2 Recommendations

It is suggested that following one or more algorithms outlined in Method Two is the best way of solving the 'trapped stream syndrome', as it predicates river capture as a basic supporting theory. Some test coding will be necessary - but it is emphasised that there is no perfect solution for this problem - rather just a series of 'least difficult' options.

Finally, it is pointed out that the suggestions in this chapter do not form a panacea for simulating erosion, although it does attempt to go as far as it can to suggest methods and algorithms backed up by Earth Science processes and landforms. The work concentrates on erosion: sedimentation is inferred rather than modelled specifically, and this area (apart from the 'assumption' that a flood plain is a 'automatically created' sedimentation feature and is therefore a by-product) needs more work. Indeed, Figure 4.10 shows the elements of a flood plain - with reference to the landform assemblage of the Lower Thames terraces. This identifies landforms that may need to be included; indeed it is probably essential that the algorithm should be adapted to include terraces, bluffs and a flood plain. However, this involves 'chronology', and although an 'imaginary' time element is of course invoked in the process response models, it is difficult to quantify - one certainly does not wish the extra complication of correlating

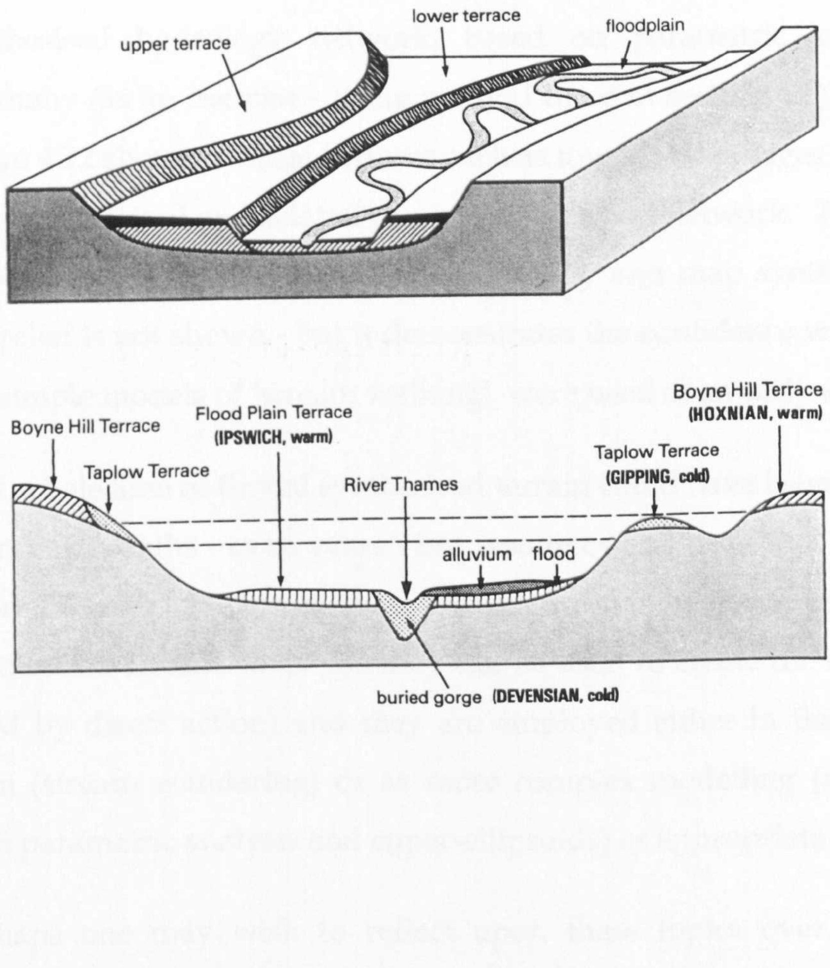


Figure 4.10 River terraces and flood plain examples (after Clowes and Comfort 1998).

synthesised terrain models with 'real world' chronology like the Hoxnian and Gipping terraces of the Lower Thames (Embleton and King 1971).

Finally, the results of river systems produced in this chapter have been deliberately 'held back' as they populate the synthesised terrain examples in the next three chapters. However, some results are necessary to show that Geoforma (and not just the 1987 FORTRAN version of Geoforma) does indeed work: Figure 4.11 shows an entirely synthesised hydrology network, based on parametric studies of Germany (as an exercise - using method three in section 4.6), whereas figure 4.12 shows cultural features such as towns and villages that have been synthesised and related to a simulated river network. This really belongs in chapter eight (human geography and map synthesis) and the relief is not shown - but it demonstrates the confidence with which the simple models of 'stream walking' were used at an early stage.

This whole area of fluvial synthesised terrain could have been explored for many months - even years - but resources and deadlines impacted upon the work. However, river systems are shown as one of the basic synthesised terrain 'tools' (as they can be used to create the simulated DEM by direct action) and they are employed either in their simple form (stream wandering) or as more complex modelling (associated with parametric analysis and super-ellipsoids) as appropriate.

Perhaps one may wish to reflect upon these topics over the next chapters - although any future work will depend on general interest and resources. However, it is fair to claim that the whole approach constitutes one of the success stories of terrain modelling (see *New Scientist, 7 September 1996*), as few (if any) workers have attempted to create synthesised fluvial terrain on the scale outlined in this chapter.

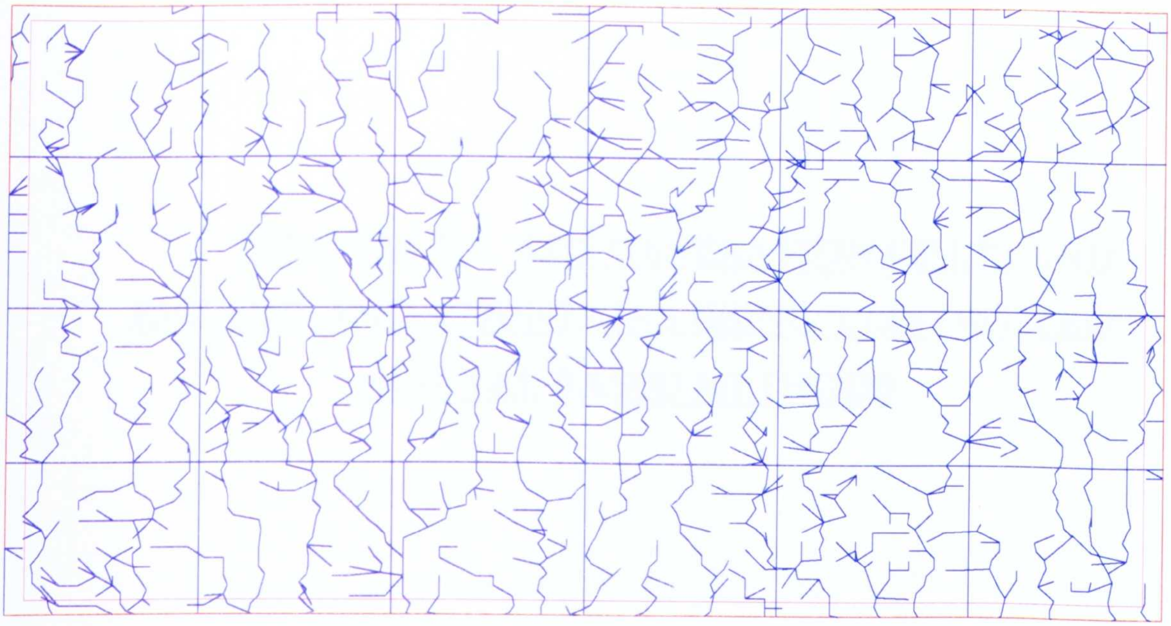


Figure 4.11 Hydrology network

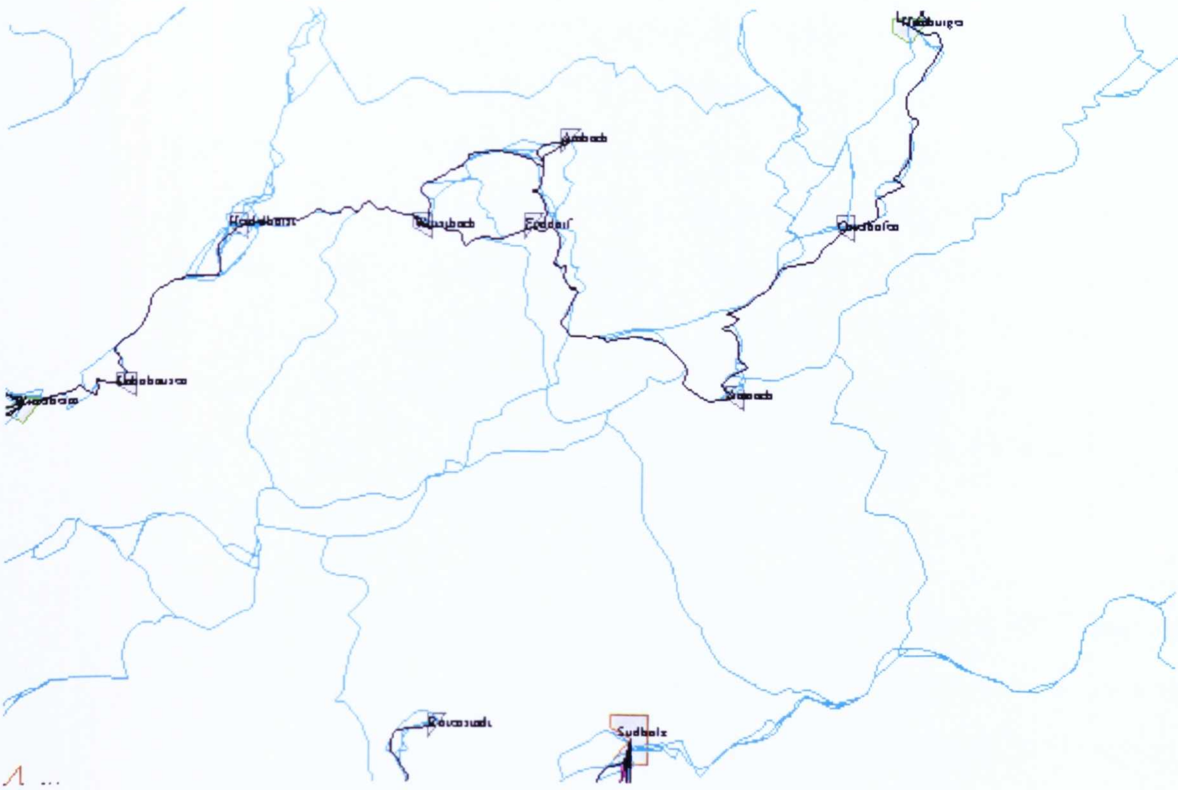


Figure 4.12 Cultural features based on drainage pattern and relief (not marked)

CHAPTER 5 : THE GENERATION OF UPLAND REGIONS AND MOUNTAINS USING 'CONTROLLED' FRACTAL-BASED METHODS

Chapter 5

The generation of upland regions and mountains using 'controlled' fractal-based methods

5.0 OVERVIEW

This chapter examines several methods, including those involving fractal-based techniques, to create upland regions. One tempting method was simply to increase the vertical exaggeration of some of the drainage basin models, but this was felt to be evading the issue: there should be some satisfactory method of 'manufacturing' upland regions and reflecting the landforms that are associated with such areas. Also, merely exaggerating the vertical axis of a DEM was felt to lessen - perhaps even destroy - the delicate geomorphologically-viable techniques that created the apparent realism of the presented DEM in the first place. Simple vertical exaggeration was indeed attempted but rejected as unsatisfactory. As a result, two areas with low or medium hills are used as exercise areas in this chapter; the Er Rif area of Morocco and part of North Europe.

The aim of this chapter, therefore, is to manufacture upland regions using the array of techniques already discussed in chapter three and used with some success in exercises. Some of the work is based on attempting to resemble igneous extrusions or sedimentary upland plateaux, although the success of this approach is critically examined.

5.1 Synthesising realistic terrain surfaces by means of controlled fractal geometry methods

Since, using various terrain evaluation and classification methods (Mitchell 1991), terrain may be broken down into basic components (landforms, man-made features etc.) methods of terrain synthesis depend upon recognising landscape components, and of course these include upland landforms. Briefly, various mathematical methods have been reviewed, compared and contrasted, and it was decided that some advantages accrued from using fractal methods, providing these were 'restrained'. Realistic '*looking*' representations of terrain and other natural objects can be obtained using affine fractal methods (Mandelbrot (1975, 1977, 1982), Peitgen and Saupe (1988) and others), although it is suggested that few - if any - geomorphologists would claim that true realism can be obtained by these methods alone - rather the reverse. However, fractals can still be useful if they are employed with care. This applies to upland regions as much as to any other type of area, and indeed scale is important (Evans and McClean (1995)) when applying the fractal-based results. More recently, workers using fractal methods have taken greater steps forward in terms of providing more useful inputs for the analysis of earth science topics (see for example the voluminous examples of fractal river basins and 'self-organised criticality' given by Rodriguez-Iturbe and Rinaldo (1997) based on field observations, as well as work by Snow (1989) and Nikora (1991)).

Terrain topology may be divided into two components:

- That of a regional nature
- That involving local fluctuations.

What is considered to be "regional" and "local" is largely subjective and depends in part upon the size of the region being examined. This effect is also examined in chapter 6 where the terms 'macro', 'meso' and 'micro' and applied with various scales and resolutions for the granite upland areas of South West England (as a test or exercise). However, the terms broadly correspond to the table of landform scales given in chapter one (Table 1.1), and would be equivalent (respectively) to type **V** for the regional terrain and between types **V** and **VI** for the local fluctuations. Linear regression analysis was used on the elevation data obtain from real-world terrain to give a basic planation surface (see the figures in chapter 3), upon which the 'local' fluctuations reside. This pseudo-planation surface formed the trend surface on which further calculations could be predicated. Calculation of the plane coefficients for this surface allows the elevation at any point on the surface to be obtained.

Then the technique is a matter of re-creating the local fluctuations in a controlled manner using control surfaces. Thus the topology creation for upland regions is similar to the processes already outlined and is composed of the following steps:-

- Establish the trend surface in accordance with analysis carried out on the terrain to be represented;
- Place control surfaces on the trend surface with a spatial distribution and shape which is characteristic of the region being generated. This is again in accordance with terrain analysis;
- Apply fractals and other models to add realistic surface detail.

5.2 Approach

5.2.1 Fractal Brownian Motion

Affine fractal methods are based upon *fractional Brownian motion*. This is an extension of standard Brownian motion, a form of 'Random-

Walk', that describes the erratic, zigzag movement of particles in a gas or liquid. The following paragraphs have fuller derivations in chapter three but some of the salient points are repeated here, for clarity.

- A random-walk path in the (x, y) or horizontal plane, starting from a given position, a straight line segment can be generated in a random direction with a random length. From the endpoint of this line segment the process is repeated.

- This procedure is repeated for any number of line segments, and the statistical properties of the line path over any time interval t can be calculated. Fractional Brownian motion is obtained by adding an additional parameter to the statistical distribution describing Brownian motion. This additional parameter defines the fractal dimension for the 'motion' path.

- A terrain surface can be obtained with a two dimensional array of random fractional Brownian elevations over a ground plane grid. The 'ruggedness' of the terrain features can be varied as explained in chapter three.

5.2.2 Random Midpoint Displacement

Fractional Brownian-motion calculations were found to be time - consuming, because the elevations are calculated using a Fourier series, which are sums of cosine and sine terms. Although Fast Fourier transforms (FFT) can be used, generations times are still rather slow. To overcome this, random midpoint-displacement methods, similar to the random displacement techniques used in geometric constructions, have been developed to approximate fractional Brownian-motion representations for terrain. The derivation and details of this technique are described in chapter three - the point being made here is that it was found to be especially useful for creating upland areas.

5.2.3 Super-Ellipsoids for generating primitive terrain features.

Although the methods described above produce reasonably realistic *looking* terrain areas, they do not generate surfaces with an inherent geomorphological validity. One way to control the placement of peaks and valleys in a fractal terrain scene - ideal for upland synthesised terrain exercises - is to use areas modelled with a midpoint-displacement method and to constrain the calculated elevations to certain intervals over different regions of the ground plane. As explained in chapter three, this can be achieved by fitting the resultant fractal closely to a series of 'control surfaces'. It was decided for the this particular part of the research project to use Super-Ellipsoids, a member of the Super-Quadric class of shapes.

It was commented in chapter three that Super-Ellipsoids seemed to bear the most resemblance to upland forms (e.g. hills and mountains). They also have a number of inherent mathematical properties which can be exploited; for example the slope of the surface may be varied from concave to convex as required. The centre point (known as our notional peak) may be displaced as required. The Cartesian representation for a Super-Ellipsoid and the corresponding parametric representation are discussed in chapter three. The resultant terrain matrix may be saved into a number of formats, including DTED or a customised file format

5.3 Exercises using above techniques: Mountain regions as 'Primitives'

5.3.1 Introduction

This part of the thesis shows some of the results that can be obtained by using the composite techniques (singly or as a phased approach).

5.3.2 Background

The fractal methods used above - particularly those depending on the definition of 'super-ellipsoids' are useful in theory. However, it was thought that if such techniques could be used 'against' real world areas, primitive surfaces may be defined and refined. This part of the chapter explains how control envelopes, super ellipsoids and trend surfaces were used to create primitive surfaces, with all the advantages of fractals but perhaps with a greater degree of freedom and control. In effect, the techniques described above to use 'controlled fractal methods' can be applied against real world areas.

Depending on the overall requirements, synthetic terrain must have certain characteristics similar to the real area of land or terrain being synthesised in order to attain the geomorphological integrity that is a basic requirement thread throughout this thesis. One of these characteristics is the nature of the "uplift features" which form the upland regions and mountains.

One way to capture the nature of the "uplift features" is by considering their statistical properties. For example height, base area, volume, shape and the distribution of the features that represent the upland regions and mountains can be considered. Such an approach was outlined in chapter 3, particularly with reference to the US Army techniques (notably the Vicksburg and Natick methods outlined in that chapter). By capturing these properties statistically the synthetic terrain can be produced using these statistics as parameters, and this was thought to contribute to a greater degree of realism, both in subjective (qualitative) and objective (quantitative) terms.

One initial step is to investigate whether patterns exist among upland regions and mountains or whether they are randomly scattered about the terrain. This, depends on geology and the tectonic and erosion history of the area, and is almost impossible to generalise since every area (particularly mountains) will have particular - perhaps even unique properties. Processes such as glaciation followed by isostatic recovery are difficult to generalise, and other factors such as climate (rainfall etc.) complicate such an approach. However it is possible to generalise up to a point if the geological history and geomorphological development of an area is known. Other question were asked such as, are the dimensions (height, length and breadth) of features apparently 'random' or do they follow some sort of relationship?

This part of the chapter considers data gathered from the Low Plateau area of Southern Germany in order to develop the key techniques. These techniques were also applied to the Er Rif (note: not El Rif) and Atlantic Coastal Plain areas of Morocco to show that they are applicable to at least one other area, and potentially to many other regions.

5.3.3 Research and military influences

Research into terrain simulation literature (chapter 2) has shown that very little has been done previously in this field, where the desired outcome can be summed up by 'something that has the *characteristics* of the targeted location or AOR, yet without being an exact copy'.

Accordingly, novel techniques have been developed using control envelopes and trend surfaces. The approach adopts the principle that upland terrain topology may be represented by placing control envelopes on a trend surface such that the statistical distribution of the envelopes and their shapes are in accordance with the real region being represented. As a safeguard period checks were carried out to view the surfaces being created in order to establish that they were developing in the desired manner for the AOR in question.

5.4 Control Envelopes

5.4.1 Overview

Control envelopes were defined for the purposes of this chapter as any three dimensional shapes that are placed on the initial trend surface. Their purpose is to provide a smooth hillside that can be 'fractalised' and eroded (in simulation) to produce a more realistic representation of the terrain. The positioning and dimensions of these control envelopes are crucial so that the synthetic terrain maintains many of the properties of the real terrain. Note that for ease of mathematical working; the axes normally represented by x and y are in this case denoted by X and Z, representing the 2D axes of the features, where Z is the long axis and X is the short axis at right angles to Z (in 2D). These are mapped onto the points of the compass (North etc.) which in turn can be transposed onto the familiar Cartesian axis set of (x, y, z) described elsewhere in this thesis. The reason for this was that it was easier to use existing mathematical notation and transpose after the results were calculated, rather than map one set of axes onto another and risk errors.

For each control envelope the following parameters were needed:

- **The height above the trend surface:** Take the real height as given on the map and subtract from this the trend surface height at this point, which can be calculated using the regression equation for the particular area.

- **The length of the plan X and Z axes:** These are calculated by measuring a sample set of control envelopes on the real terrain. The Z axis is always the longer of the two axes.

- **The Offset of the highest point:** This is given as a proportion of the length of each axis and is obtained by observing a sample of control envelopes in the real terrain.

- **The orientation of the control envelope:** This is the angle between the long (Z) axis and north. This again is calculated by observing a number of control envelopes on the real terrain.

- **The number of control envelopes per cell:** This can be calculated by taking individual cell samples and counting the number of control envelopes for each. The mean of these observations can then be calculated and used.

As long as the sample of control envelopes that are observed is large enough the height, length of the X and Z axes, offset of the highest point and angle of rotation can be said to follow a Normal distribution. Due to the nature of the number of control surfaces per cell, this data can be reasonably said to follow a Poisson distribution, which can then be approximated to the Normal distribution. For each parameter the mean and standard deviation are required.

Note - For a Poisson distribution:

$$\textit{mean} = \textit{variance} = (\textit{standard deviation})^2$$

5.4.2 Placement of Control Envelopes

The location of the control envelopes within the terrain has also to be investigated. Nearest neighbour analysis can be used to calculate the index to the spatial pattern (R), using formulas 1 and 2.

$$R = \bar{d} / \bar{\delta}$$

(1)

Where $\bar{d}$ = the observed mean distance between nearest neighbours and:

$$\overline{\delta} = \frac{1}{2}\sqrt{A/n}$$

(2)

A = the area of the terrain being analysed and n = the number of control envelopes in the studied terrain. R can vary between 0.0 and 2.15. A value of 0.0 means the points coincide and are separated by a distance of zero, 1.0 means there is an ideal random distribution of points and values around 2.15 indicates that the mean distance between points is maximised, causing a perfect hexagon pattern to form.

As the control envelopes are intended to be in a "coarse" or "primitive" state before erosion is applied, their shape can be simplified. This means that geometric shapes (such as super ellipsoids) can be used. This not only makes calculations easier but is a justifiable practice due to the aim of obtaining a 'pre-fractalised and pre-eroded landscape'. Therefore even though the initial terrain might look 'too perfect' the final outcome should be a realistic terrain that satisfies the statistical and subjective requirements.

For the Er Rif AOR, the control envelopes were approximated to what were deemed to be hard crystalline and limestone rock outcrops on inspection of geological maps. Therefore there is some correlation between the geology and the relief, although it is stressed that this is (a) synthesised terrain and (b) an estimation - one might be brutally honest and say a rationalisation - only. However, at least it introduces geology into the model, if only at a superficial level (see the similar arguments for fluvial erosion in chapter four).

5.5 Trend Surface

5.5.1 Terminology, use and abuse

Trend surfaces seem to be relatively 'unfashionable' term at the moment. A sample of several standard geomorphological textbooks at random (including Small 1990) failed to find any reference to the term in the index. However, for the purposes of this thesis, a trend surface is defined as a generalised terrain primitive, which can be created as a mathematical topological surface by a variety of methods.

5.5.2 Background

When trying to observe the dimensions and distribution of the so-called uplift features and mountains, all that can be seen is that which occurs above ground. Therefore even though heights given are above some sort of reference datum plane, the techniques being used meant that the shape of the control envelope could only be observed from a certain height upwards, for example 300 metres. The actual size of the control envelope below this height could not be observed. Thus when placing control envelopes on the terrain they cannot be placed on a zero level as the observed control envelopes are not on a zero level.

One way to get around this problem is by defining a trend surface upon which control envelopes can be placed. The trend surface simulates the underlying level that the control envelopes 'sit upon' in the real terrain. Thus the dimensions of the observed control envelopes can be used in the simulation process.

To recreate the trend surface of the 'actual terrain' in the 'synthetic terrain' the corner heights of the actual terrain trend surface are required. These heights cannot be obtained by just observing the corners of the terrain, but by observing heights throughout the area being synthesised. These heights must be 'low heights', that is they are on the trend surface only, not on a control envelope. By noting the X and Z co-ordinates of these heights regression analysis can be used to calculate the heights at the four corners.

5.6 Applying The Trend Surfaces And Control Envelopes To The Low Plateau Area of Southern Germany (Exercise One)

The first exercise using upland features (or uplift features, as the sponsor would have it) took place using TPC sheets and larger scale maps of parts of Northern Europe, Specifically, the Low Plateau area of Southern Germany was chosen, partly for its military value in the 'Cold War' and partly on the grounds that several participants in the work were familiar with the region. This AOR is an area of undulating countryside dissected by winding river valleys.

5.6.1 Trend Surface

For the Low Plateau area of southern Germany the heights of the corners of the trend surface were calculated as shown in figure 5.1, where the upward arrow represents X and the left facing arrow represents Z (note that this co-ordinate system was transposed to the right-handed (x,y,z) set used for presentation of DEMs and DTMs after the initial calculations were carried out). This may seem an over-simple diagram but in fact it is vital to 'anchor' the primitive in terms of its area and the elevation at each corner.

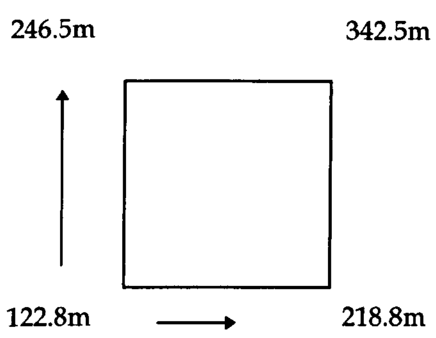


Figure 5.1 Trend Surface Analysis for Low Plateau Area of Germany

Note - the heights at each corner are the heights of that corner above sea level.

Height of Control Envelopes: The mean of the observed heights, above the trend surface, was found to be 238.21 metres. The standard deviation of these heights was found to be 62.32 metres.

Thus to reproduce the heights of the control envelopes random numbers can be used than follow a normal distribution with mean of 238.21 metres and a standard deviation of 62.32 metres. To calculate the actual height above zero the trend surface height at the points on the control envelopes have to be calculated, and then added to this calculated height.

Plane equations can be used to calculate the trend surface height at any point (x, y) on the plane, these formulas are:

$$A = z_1(y_2 - y_3) + z_2(y_3 - y_1) + z_3(y_1 - y_2) \qquad (3)$$

$$B = y_1(x_2 - x_3) + y_2(x_3 - x_1) + y_3(x_1 - x_2) \qquad (4)$$

$$C = x_1(z_2 - z_3) + x_2(z_3 - z_1) + x_3(z_1 - z_2) \qquad (5)$$

$$D = -x_1(z_2 y_3 - z_3 y_2) - x_2(z_3 y_1 - z_1 y_3) - x_3(z_1 y_2 - z_2 y_1) \qquad (6)$$

$$y_i = \frac{(-Ax_i - Bz_i - D)}{C} \qquad (7)$$

Where A, B, C and D are the plane coefficients; x_i and z_i are the x and z co-ordinates of the desired point; y_i is the trend surface height at (x_i, z_i).

Similarly, (x_1, y_1, z_1), (x_2, y_2, z_2) and (x_3, y_3, z_3) are the three dimensional co-ordinates of three known point on the plane, in this case three of the corners.

Z and X Axes length: The analysis showed no relationship between the Z and X axes. There was also no relationship between either of the axes and the height of the control envelope.

The Z axis is always the long axis of the control envelope. This axis had a mean of 8430m and a standard deviation of 1376.025m. The X axis is always the shorter axis and for the observed area it had a mean of 4230m and a standard deviation of 1260.555m

Again the Z and X axes lengths for each control envelope can be calculated by the generation of random numbers that follow the normal distribution with a mean and standard deviation as given above.

Offset Of The Highest Point: For the sample set from the Low Plateau of Southern Germany the data gave the following data. The offset in the direction of the Z axis had a mean of 0.41% of the Z axis length with a standard deviation of 20.45% of the Z axis length. The offset in the direction of the X axis had a mean of 12.44% of the X axis length and a standard deviation of 22.14% of the X axis length.

The offset can be calculated by generating random numbers that follow a normal distribution with the relevant mean and standard deviation as given above.

Orientation: For the sample set from the Low Plateau of Southern Germany this data had a mean of 10 degrees and a standard deviation of 20.5 degrees.

To calculate the angle of rotation for a control envelope in the synthetic terrain generate random numbers that follow a normal distribution with a mean and standard deviation as given above.

Distribution: For the sampled Low Plateau area of southern Germany the mean was found to be 11.125 control envelopes per 10 km x 10 km square (i.e. 100 km^2). The R value for the location of these points was found to be 1.30.

Therefore the number of control envelopes to place in each 10 kilometre square in the synthetic terrain can be calculated by generating random numbers that follow a Poisson distribution :

(mean = 11.125, standard deviation = SQRT(11.125)).

Obviously only whole control envelopes can be placed and so the integer of the produced number is used. Due to the R value the control envelopes can be placed at random co-ordinates on the terrain. In addition to the low plateau area of Southern Germany, three other land formations of Germany have been characterised and processed.

Super Ellipsoids: For the initial creation of the synthetic terrain all the control envelopes have been produced as super ellipsoids. These give control over the general shape and slopes of "uplift features" and discussed in more detail in chapter three.

All the statistical values produced are the result of a sample and have been treated as such. They are not the true mean, standard deviation, maximum and minimum of the parameters, but they are a good estimate due to the relatively large size of the sample. Thus they can confidently be used in the synthesising of terrain.

5.7 Applying the developed techniques to Er Rif area of Morocco (Exercise two)

It was found that the techniques used statistically to capture the Low Plateau area of southern Germany could quite easily be used to capture statistically the separate areas of Morocco. The Er Rif area of Morocco is a mountain range in the North east of the country. This area runs along the Mediterranean coast and is mostly made up of limestone. For the exercise a TPC (Tactical Pilotage Chart) at a scale of 1:500,000 was used for the appropriate areas. A trend surface was imposed with control envelopes upon it. The heights of the corners of the trend surface are shown in a sketch (see figure 5.2).

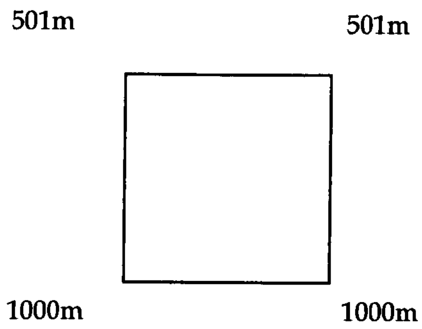


Figure 5.2 Level Trend Service Analysis for Er Rif Area of Morocco

Again values for the control envelopes could be reproduced randomly, following a relevant normal distribution, and the axes are the same as for figure 5.2.

The heights of the control envelopes had a mean of 896.09 metres and a standard deviation of 353.22 metres.

The length of the Z and X axes were again found to have a relationship with each other and with the height. The Z axis had a mean length of 13100m and a standard deviation of 6209.45m. The X axis had a mean length of 10100m and a standard deviation of 5102.08m

The offset had a mean of -6.57% and a standard deviation of 11.6% in the Z axis direction, and a mean of 17.74% and standard deviation of 9.81% in the direction of the X axis.

The observed rotation of the control envelopes in the real terrain had a mean of 39.375 degrees and a standard deviation of 15.21 degrees.

The distribution of the control envelopes again followed a Poisson distribution with a mean and variance of 1.057 envelopes per 10 km X 10 km square. Again this distribution can be approximated to the

Poisson distribution to produce the number of control envelopes per 10 km X 10 km square (100 km^2) in the synthetic terrain. The calculation method follow those outlined in 5.6.1 above.

5.8 Results of the various techniques to produce upland regions

Using the above techniques, three areas of Poland (overlapping with other nations in Central Europe) were similarly analysed but the results were classified according to military security and most have been withdrawn from the research thesis. However, the results were satisfactory and the client (DERA) expressed their satisfaction in the appropriate meeting minutes during 1996.

The results from the two exercises are shown in the following diagrams, along with some comparative exercises of upland regions based on the Er Rif area alone, but using different techniques (such as Fast Fourier Filtering or FFT). First, Figures 5.3, 5.4 and 5.5 show the underlying trend surface (Germany and a part of Poland), followed by an example of a 3D view of a large area (Fig. 5.6) and finally the upland area shown as a 2D map as outlines - these are not contours but mark the extent of each feature (Fig. 5.7). This entirely synthesised terrain was released by DERA (copyright DERA) and shows how the trend surface method was used to produce 3D and 2D pictures based on DTED data.

Importantly, the upland topography was created using super-ellipsoids (see Figure 5.6 and 5.7). The 3D view in Figure 5.6, which appears elsewhere in this thesis in slightly different format and to demonstrate a different point, uses colour to show relief, with blue (lowest areas) to red/yellow (highest areas). This area was based on the TPC and ONC charts of North Africa.

Next, Fast Fourier Filtering (FFT) techniques were used to create three successively refined views of an 'imaginary' upland area (see Figure

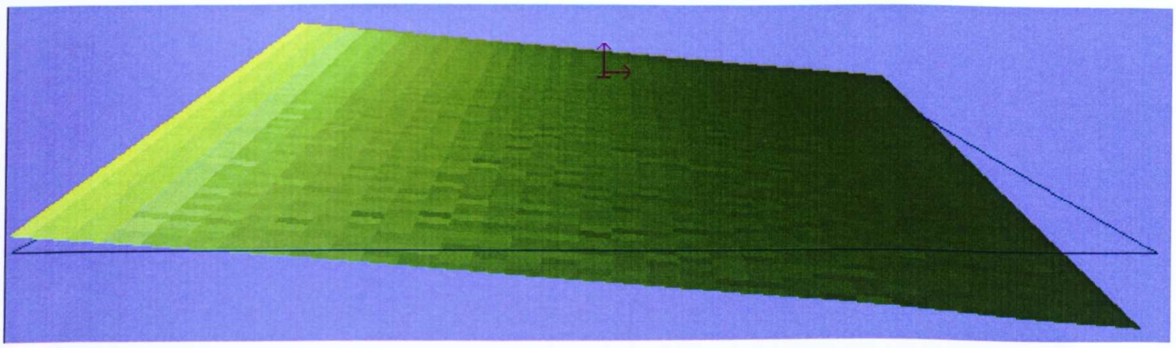


Figure 5.3 Underlying trend surface

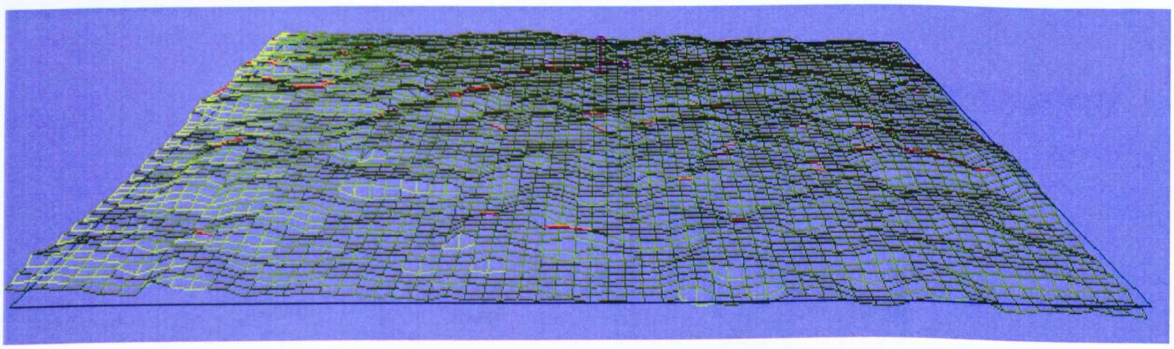


Figure 5.4 Elevation matrix

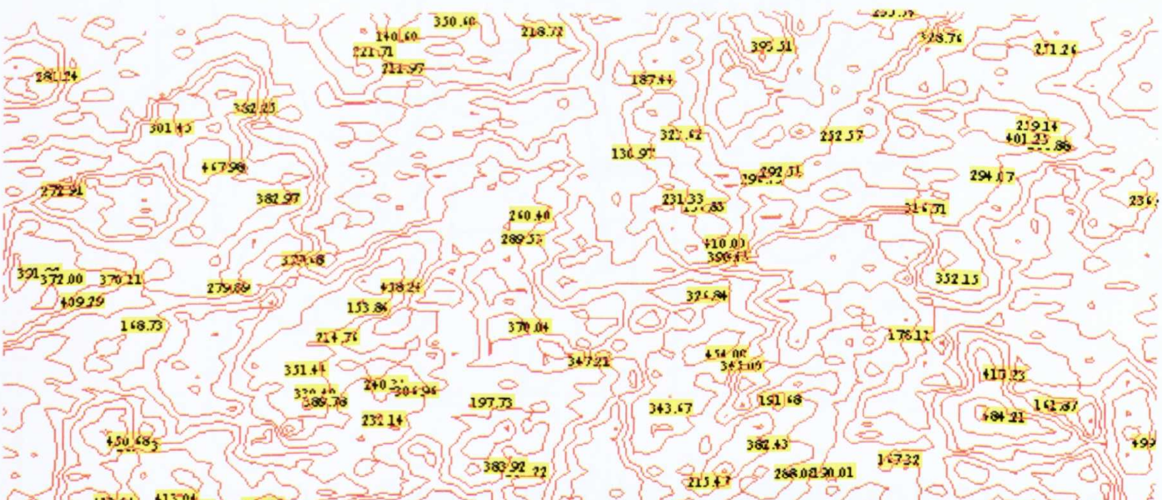


Figure 5.5 Contour lines

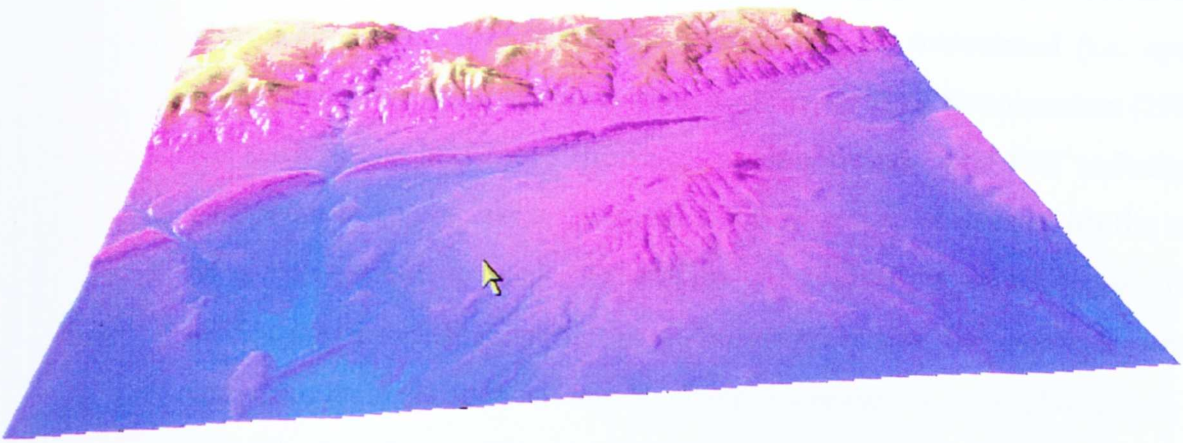


Figure 5.6 Illustration of terrain topology

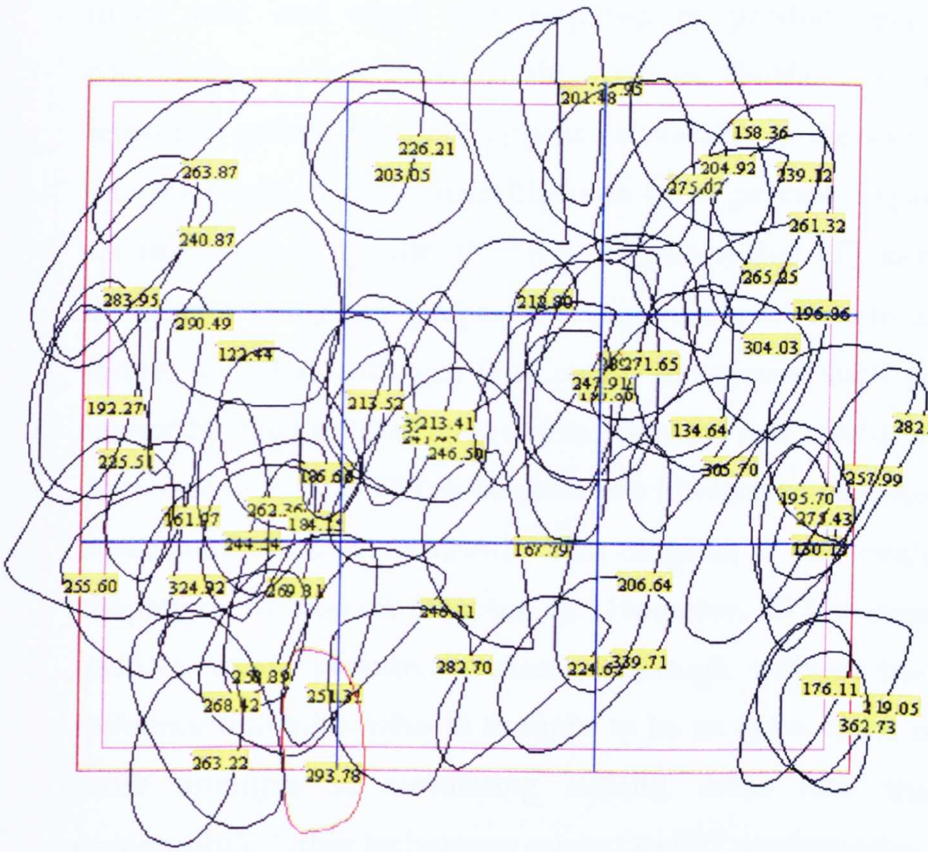
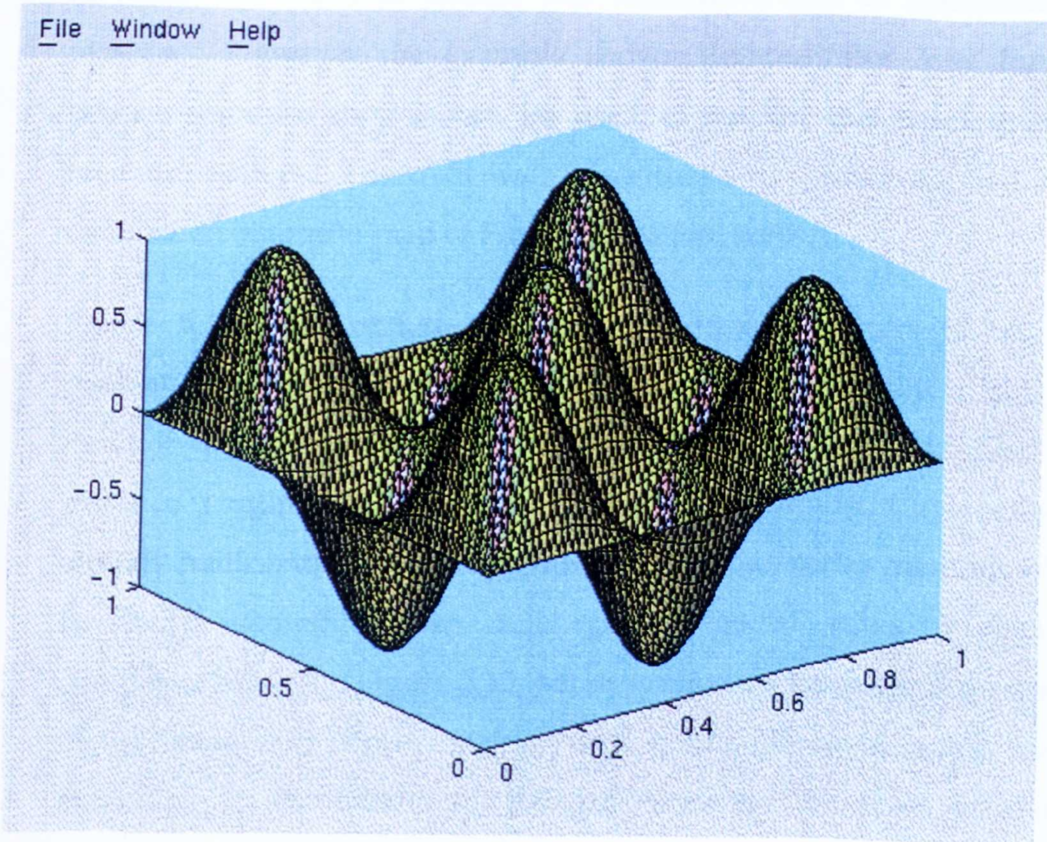


Figure 5.7 Super-ellipsoid shapes distributed on trend surface

3.19 in Chapter 3). This is not based on any part of the world but shows what FFT and filtering methods can do unassisted (i.e. apart from their base computations - see authors such as Kraniauskas (1995) for derivations and more thorough explanations). The FFT technique can provide a very fast orthogonal decomposition of data (with the use of a 'thresholding' rule to obtain a smoothing procedure). The smoothing procedure, sometimes causes problems, for example when the underlying function has a sharp increase in one place, but is smooth elsewhere. The results for synthesised terrain are promising but were felt to have the 'mathematical' function drawback in that much trial and error was required to produce even the fairly convincing example shown in the diagram. By this it is meant that the terrain *in general* does not appear as realistic as the examples where parameterisation and superellipsoids (plus process-response models) are used as a composite 'fit'. It is suggested that FFT is no match for the careful, composite preparation of synthesised terrain as mentioned above, and that although it is rapid, techniques such as FFT ***alone*** cannot be used to 'dial up' an area from the real world without some degree of fortuity (FFT can be used as a filtering mechanism for fractal-based mathematical routines). This diagram is also evaluated in the chapter on validation (chapter 9). However, FFT techniques can be used to create primitive surfaces, although without the parametric influence that adds what is thought to be an extra order of realism to other attempts at simulating upland areas (see the following paragraphs). Other techniques related to FFT mathematics, not used in the thesis but demonstrated for possible upland synthesis are represented by wavelets (Figure 5.8), although it is suggested that significant further adjustments needs to be made before the example shown enters the realm of realism (this is not to dismiss wavelets as a potentially useful method - it merely shows a typical example in an upland context).



Gridsize (65 x 65), 4225 datapoints, j=6.

Figure 5.8 Terrain Synthesis using 'eggbox' wavelet function (source: http://www.oslo.sintef.no/wavelets/example1.html

The river walk algorithm (described in chapter four) was applied to a high plateau area, and the results of successive erosion (leading to a meandering river in a flood plain) are shown in Figure 5.9. This was 'borrowed' from a textbook block diagram as the original (almost identical) 3D view, in colour, was withdrawn due to classification reasons. However the example shown demonstrates how fluvial process-response models can be used to cut (in this case) upland meander valleys. The river walk algorithm was instead applied to a simulated composite map of North Africa (see below).

Figure 5.10 gave perhaps the most impressive results of all, in presentation terms. First, the exercise was repeated with a 'single-iteration process response fluvial model in operation', weighted to produce marginal erosion so as not to upset the implied fluvial effects already built in to the model by means of the parameter methods (this is always something one must guard against when producing composite models). Figure 5.10 therefore shows a mountainous region of an 'imaginary North Africa', with a full 2D topographic map, extending in increments of 100 km^2 squares (the scale is about 1:500,000), and includes some features not treated until later chapters (roads, settlements and other features which are described in chapter eight). It was felt to be a useful exercise to demonstrate this map at this stage - before 'human geography' had been dealt with - as it is felt to be such a good example. Indeed, the results of the exercise are good, one might say almost spectacular, considering this is entirely synthesised terrain.

Some analysis of this synthesised terrain exercise (exercise 2) is merited. First, the simulated river pattern corresponds ideally with the simulated mountainous topography, and at no place are there any 'anomalies' (crossing contours, streams wandering uphill or in an 'unrealistic' manner. Some streams simply flow down the side of the

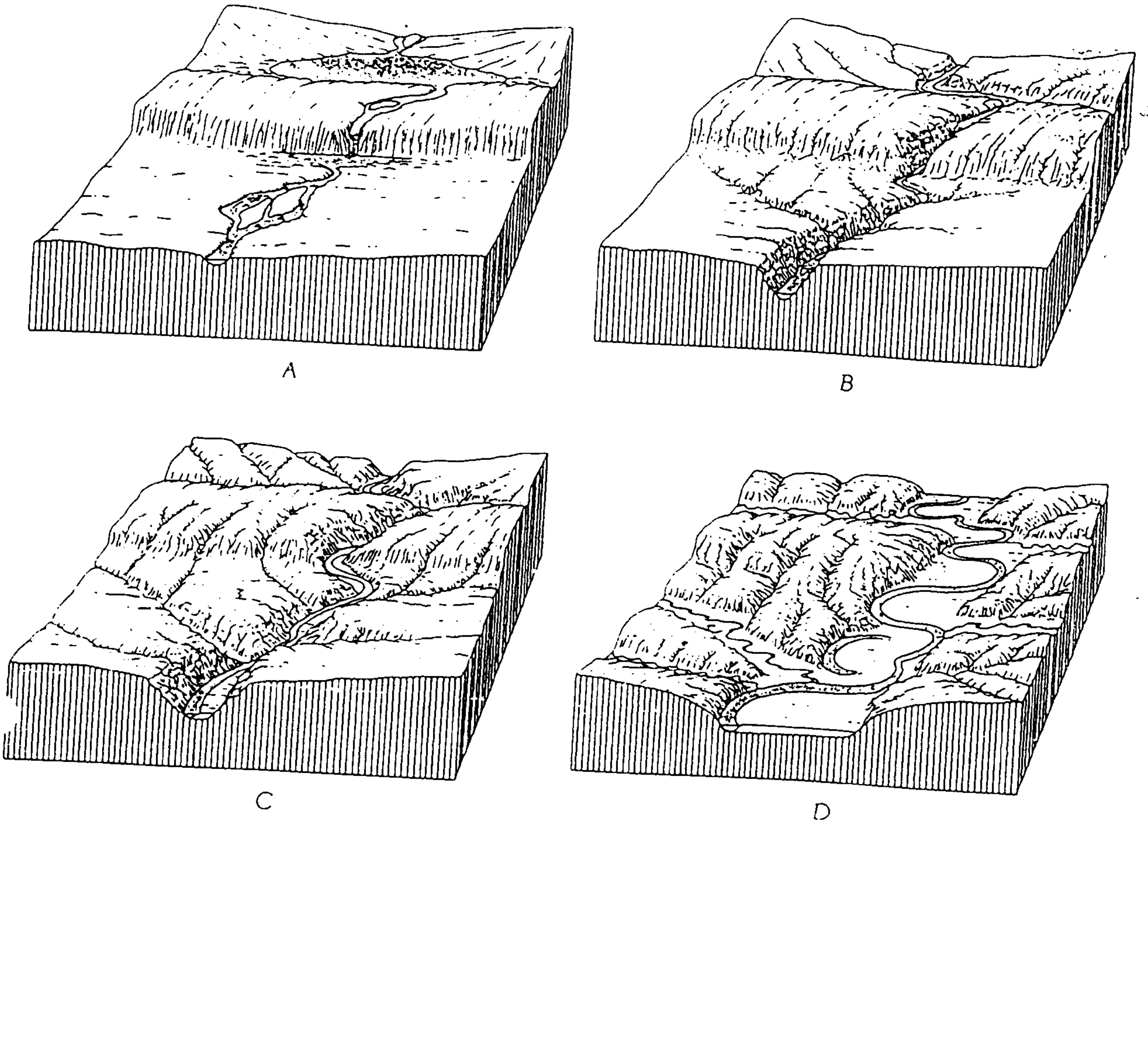


Figure 5.9 Topographic erosion model using process-response fluvial model

slopes, whereas others flow in small valleys. The lack of valleys for all streams was because the process-response stream model was 'set up' to produce minimal erosion (in order to 'preserve' the simulated upland areas) and also because the area is relatively arid, and so some streams would be ephemeral and might be expected to inhabit small or barely recognisable valleys. Indeed, many of the streams would probably be dry courses for much of the year, but are marked anyway. This may sound like a rationalisation, but it was predicted accurately before the map was produced, to the delight of both the author and the sponsors. The 3D view of the same area, based on super-ellipsoids is also spectacular, considering it is entirely synthetic. Interestingly, the river pattern is radial - indeed it is virtually annular, as described by Way (1968) - and even though this is partly fortuitous the radial drainage correlates well with the simulated rounded massif upland regions.

In other words, as part of the research, the effect of creating higher resolution DEMs was considered by 'processing' real-world DTED data. This is one way of approaching the problem, but it can be argued that it is not synthesised terrain *sensu stricto*, nor does it solve the problem of producing terrain in areas where no DTED data exists (such as potentially hostile areas which have not been surveyed except at a very small scale), since the source is a TPC or ONC map (or similar).

5.9 Limits for Random Numbers From A Normal Distribution

5.9.1 Treatment

The height, Z and X axes lengths, angle of rotation and number per cell are all produced using random numbers with a normal distribution of a given mean and variance, depending upon the analysis.

Using the modified rejection method a random number, *r*, between the upper and lower limits of a standard normal distribution (mean = 0, standard deviation = 1) is generated. This random number can then

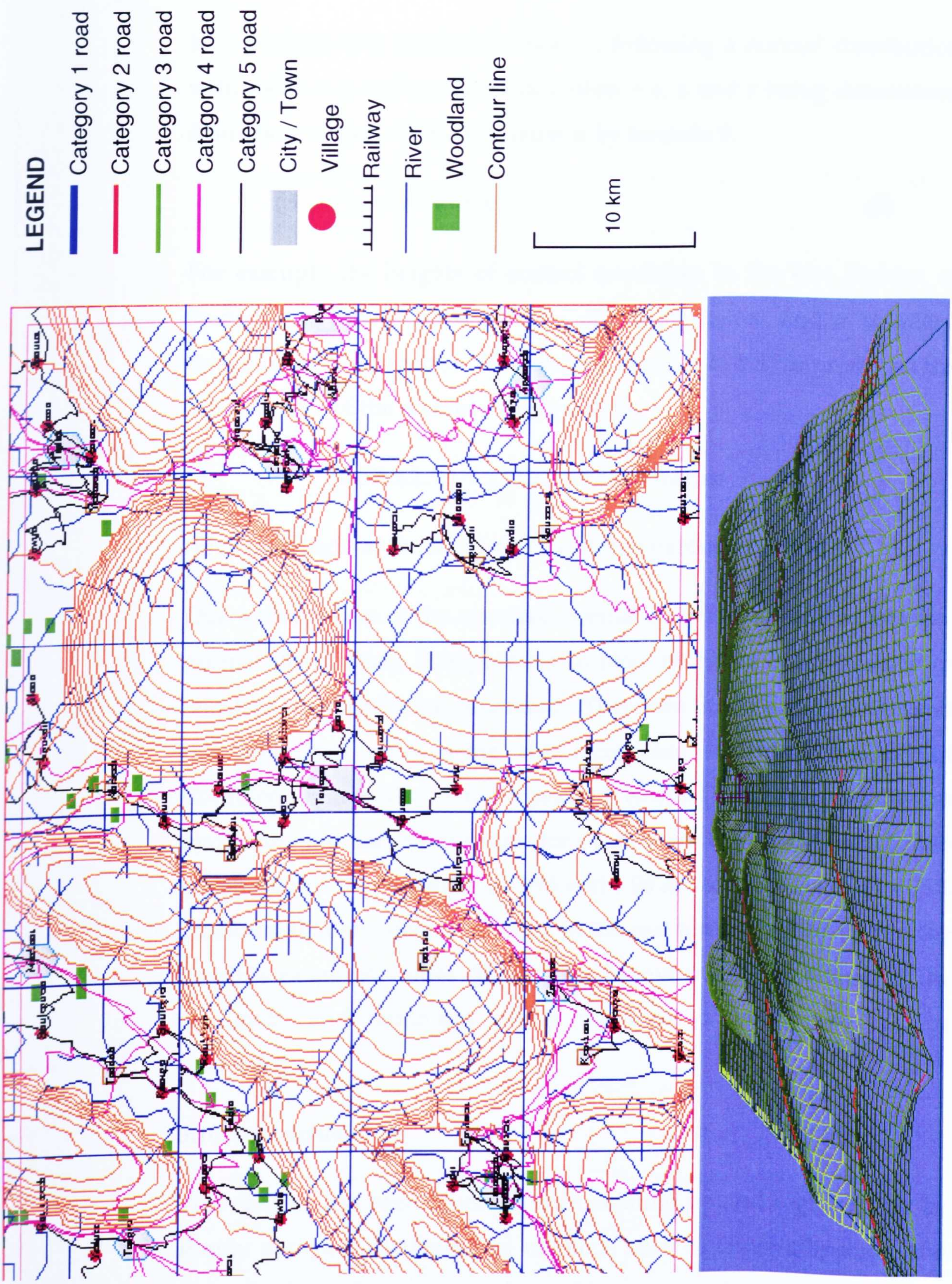


Figure 5.10 Mountainous region of 'Imaginary' North Africa

be converted to a random number, j, following a normal distribution with mean = x and standard deviation = s, x and s being determined from the analysis. This conversion is by formula 8.

$$j = (r \times s) + x \tag{8}$$

For example the heights of control envelopes in the low Plateau of Southern Germany have a mean of 238.21 metres and a standard deviation of 62.32 metres. If a random number of 0.57 is produced the actual height of the control surface will be:

$$(0.57 \times 62.32) + 238.21 = 273.73 \text{ metres}$$

(plus the height of the trend surface at that particular point)

Due to the nature of the standard normal distribution, and in fact any normal distribution, it is possible to have infinitely large positive or negative numbers being generated. Therefore limits had to be set and this has been done using the recognised statistical method of Confidence Intervals. For a standard Normal distribution different maximum and minimum values for r can be set to give different levels of confidence. For example if -1.96 and 1.96 are set then we can be 95% confident that any observed value in the real terrain will be within the possible range of values (j) that can be returned. By adjusting the maximum and minimum values the level of confidence can be controlled.

5.10 Conclusion

This chapter has been involved with creating upland regions, first by simply applying mathematical methods such as super-ellipsoids, and secondly by using parametric analyses to synthesise areas in the Middle East, North Africa, Germany and Poland.

No geomorphological process-response model was written explicitly for the upland areas - other than adopting the fluvial model - although this is covered, for a limited geographical area in the next chapter on the granite uplands of South West England. This is due to several reasons:

- The (military) sponsors were satisfied with the upland DTMs produced - which were presented to them as maps and in DTED data.

- Fluvial process-response models (as described in chapter four) were found to be successful in creating drainage systems in upland regions (see figures 5.9 and 5.10) and more sophisticated models could be applied if desired.

- Some of the work was classified and no diagrams are available because of international tension at the time of the research (1994 to 1997) which could have affected British forces. Although this tension may no longer apply, regrettably the diagrams of central Europe are simply not available due to military restrictions and there is no possibility of regaining or presenting them in the near future.

- The upland regions were judged to be successful - not just because the client was satisfied - but because the views looked realistic. As important, the views turned out largely as predicted, after some fine tuning. However it was felt that much more geomorphological research could have been done, had there been time, and this topic awaits further research - perhaps combining the existing models with geomorphological models to create escarpments, higher mountain ranges, etc. Moreover, the geology needs to be examined in more detail, since a generic model is not needed for a synthesised terrain on a dial-up method. This simplifies the modelling of the effects of geology on terrain somewhat (i.e. by correlating limestone massifs with hill structures at the synthesised terrain version of Er Rif) but it is only a first step.

- Other upland diagrams are given throughout this thesis - like the work on fluvial processes they are not confined to the chapter of origin but are used elsewhere (such as for human geography), for composite maps or for demonstration purposes.

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CHAPTER 6 : GRANITE UPLAND LANDFORMS BASED ON SW ENGLAND

Chapter 6

Granite Upland Landforms based on SW England

6.0 THE GRANITE UPLANDS OF SOUTH WEST ENGLAND

6.1 Introduction

This chapter assesses the creation of synthetic digital terrain models for granite regions - with the geology and physical geography of the granite upland or moorland scenery of South West England used as a source area (Edmonds *et al* 1975, Charman *et al* 1996). This region includes the well-documented areas of Bodmin Moor and Dartmoor, as well as the other granite areas (Lundy Island, The Isles of Scilly, coastal areas and isolated outcrops such as in the Luxulyan, Carmenellis and Carn Brea areas etc.) all of which have a distinctive appearance at the macro-scale. Indeed, all of the upland areas of South West England are mostly granitic apart from Exmoor.

6.1.1 Reasons for choosing South West England

The physiographic characteristics of the granite uplands of South West England were used both as a study and a validation area. The area is well documented (Small 1990, for example, devotes part of a chapter in his textbook to granite landforms on Dartmoor). In this instance, the author already had full 1:25,000 scale map coverage, plus a collection of air and landscape photos, backed up by an intimate knowledge of the region (see Griffin 1977, 1979). Moreover, the terrain evaluation techniques described in chapter 3 were thought to be potentially more efficacious in cases where the landscape is familiar to the users attempting to model it. Therefore, parts of South West

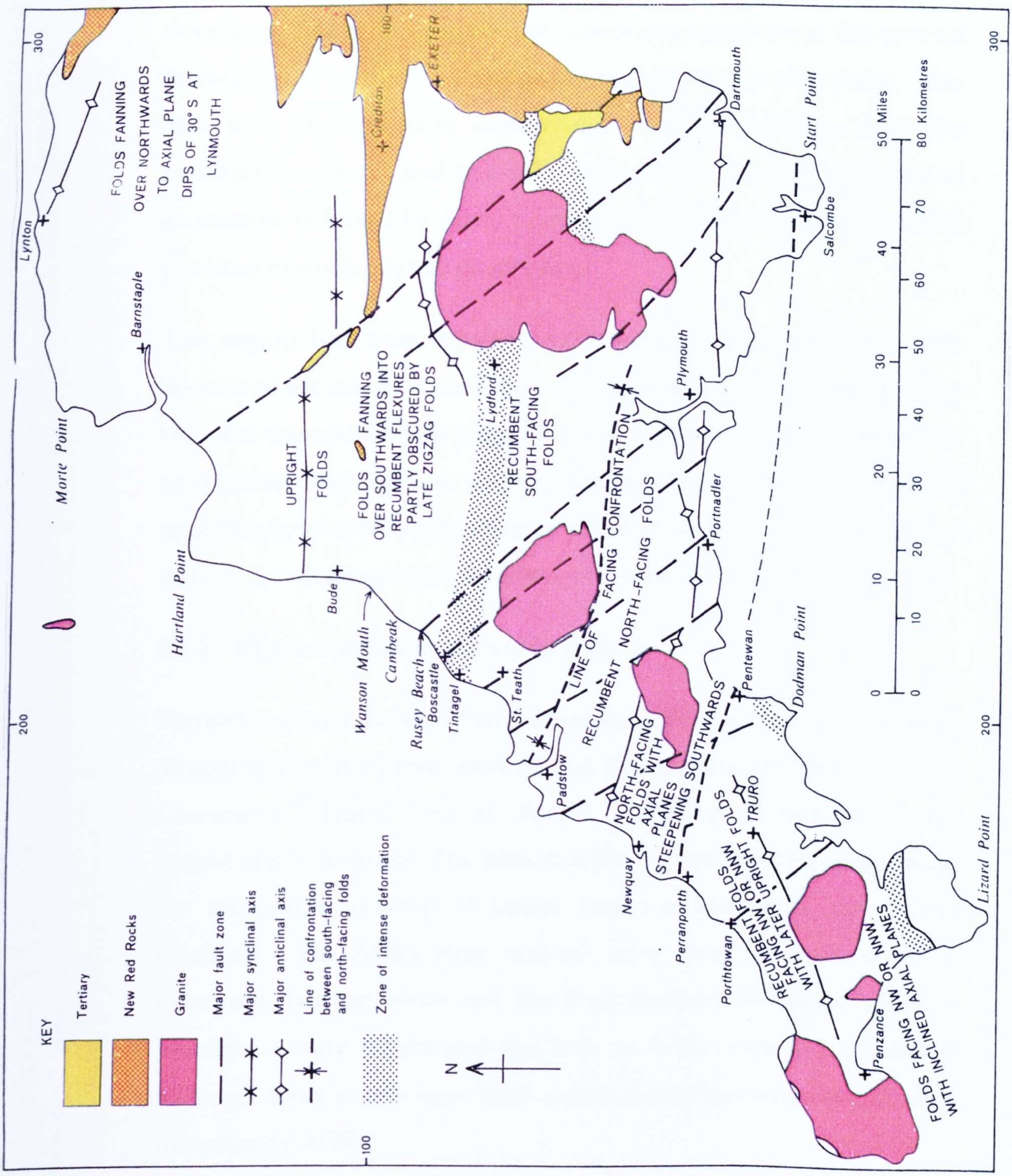


Figure 6.1 The Study Area for South West England (after Edmonds *et al* (1975)

England can be regarded as a good 'test and validation' area that was done as a 'free will' exercise and which can supplement the general knowledge of synthesised terrain being presented in this thesis. The area was, perhaps more importantly, to allow exercises done for reasons of academic and personal interest rather than being linked to an exercise enforced by Army training necessities, as have been many previous examples of terrain synthesis.

This region had been selected, as was mentioned in chapter one, because of the author's familiarity with the landscape, and the fact that this was thought to help judge whether synthesised terrain based on South West England was realistic. Finally, the chapter represents an opportunity to synthesise terrain at different scales - including 'micro-terrain' (i.e. dealing with landforms on a scale of 10 to 100s of metres).

6.1.2 Characteristics of the Study Area

Figure 6.1 shows the study area, emphasising the granite and regional structural features (from west to east the plutons are: *West Penwith, Canmenellis - Lizard Area, St. Austell - Luxulyan, Bodmin Moor* and largest of all: *Dartmoor*. The Isles of Scilly are not denoted on this map but the granite outcrop of Lundy Island is marked in the Bristol Channel). The AORs were selected from more detailed maps of Dartmoor, Bodmin Moor and the West Penwith (the most westerly pluton). Lundy Island and the Isles of Scilly were not modelled although some points have been made about these areas as possible future study AORs.

Granite is an igneous rock comprising feldspar (which is a principal component and helps determine the colour), quartz, biotite and/or muscovite mica as well as trace minerals such as magnetite, apatite and hornblende. Many rocks are incorrectly referred to as 'granite' or 'granitic' (Barnes and Noble 1960) but the examples found in South West England are 'true' granites, albeit with some variations.

Granite landscapes - particularly uplands where there are outcrops - can give rise to interesting and distinctive scenery. It was the tors of Dartmoor that have attracted the attention of many geomorphologists, including Linton (1955), who pronounced them as relic features and attributed their formation to deep-weathering associated with the frequency of the joints and other structural components in the granite bedrock. For example, where the vertical joints (the Q and S joints of Cloos' 1936 classification) are grouped with relative frequency, Linton alleged that the rock is more vulnerable to weathering and is therefore more liable to break down, whereas less-fragmented areas of massive granite, with fewer joints, will be more resistant and have often formed into the distinct tower-like outcrops known as 'tors'. Other, similar theories for tor morphogenesis have been advanced by workers after Linton which differ mainly in points of detail (e.g. Palmer and Neilson (1962), Waters (1964), Twidale (1971 and 1976) and others).

Put simply, tor development is a form of differential weathering on a large scale - both in distance and time. The L joints - the pseudobedding planes of Cloos (1936) - give rise to the sub-horizontal planar features that help make up the tors. Indeed, much of the scenery on Dartmoor and Bodmin Moor at all scales takes its pattern from the underlying geological structure, notably the joints in the granite, as well as from other types of strata forming differential strengths or weakness that have been exploited by drainage systems. The sharp break of slope on the east of Bodmin Moor, for example, where the granites give way to 'country' rocks, is an area of small but spectacular waterfalls and gorges. Similar areas can be traced on the edge of Dartmoor, while the coast of Lundy is characterised by tors crowning impressive, sheer cliffs of nearly 130 m (400 ft).

It was felt that since the scenery is so distinctive and well documented at almost every scale, some parts of the granite areas of South West England would be a good 'target' landscape type to attempt to synthesise. This also has the aim that because the landscape is well known then subjective validation could be easier than - for example - an anonymous or non-descript area unfamiliar to all (except perhaps to those who live there or who have had cause to study it for some reason). It is therefore proposed that the scenery of Dartmoor and Bodmin Moor is more 'distinctive' than - for example, non-granite upland regions of otherwise similar altitude and environment, in Wales, North England or Scotland (although of course other rocks - such as limestone - can form tors - Holmes (1972), Goudie (1990) - and indeed similar tor forms can be found in the granitic mountainous areas of Scotland, such as near Ben Avon in the Grampians) and in other areas in the world - such as the granite tors of the Sudeten Mountains (Jahn 1974) or the Inselbergs of Brazil (Freise 1938).

6.2 Map scales (and resolution) adopted

The map scale, and therefore the resolution, of the terrain synthesis products is tackled in three groups or stages:

- **Macro** (using 1:100,000 and 1:50,000 scale maps) - this covers long-distance 'views' of the landscape and, if the resultant DEM was translated into a 3D perspective, would be the equivalent of a picture postcard of Dartmoor taken from a high viewpoint. At this scale some parametric techniques were used to define the landscape facets. The idea here was to try to gain a panoramic view of 'the Dartmoor or Bodmin Moor from another universe' - in other words, an exercise in attempting to resolve the usual paradox of producing a view of geomorphologically-sensible and broadly recognisable terrain that is nonetheless completely fictitious.

- **Meso** (or Medium - using 1:50,000 maps and 1:25,000 maps) which would model groups of tors and possibly one or more small drainage basins. This could be derived from the macro-terrain examples merely by enlarging the scale and adding more detail, since the Vicksburg-Natick composite method did not produce satisfactory initial results for terrain at this scale (which was approximately equivalent to the coverage of 1:25,000 OS Pathfinder sheets).

- **Micro** (using 1:10,000 or larger scale map) which would examine the micro-topography of an individual tor, summit or outcrop complex. This scale included the attempted simulation of many smaller landforms and it is explained in greater detail later in this chapter. Generally this thesis is not concerned with micro-features but this chapter gives a brief examination for the purposes of comparison.

The approach for the first two scales or groups follows the approach or methodologies outlined in the previous chapters. This approach is itself represented by a set of programs that form part of the Geoforma suite of software. However the micro-terrain at the level of metres and tens of metres (individual tors) is difficult to trace from a map, so aerial photographs, standard photographs and (Imperial) measurement of actual features are used.

In summary, the terrain synthesis exercise based on granite scenery in South West England was attempted for several reasons:

- The region is well-documented and well known to the author

- The region has a distinctive topography which will aid validation and assessment of 'fit for purpose' decision-making

- Although the region may be thought to have a distinctively 'English' feel, the basic elements of the physical topography have also been encountered almost wherever granite landscapes are found (e.g. Scotland, Norway, South East Asia, South Africa etc.) and therefore other world regions may perhaps be modelled with only minor variations.

6.3 Methods

The techniques used included some parametric methods of analysis, some application of fractals (to image the self-similarity of the tor forms at a very detailed level) and random-walk techniques to create stream valleys, with the intention of creating a mixture of valley side and summit tors. Some freehand styling and editing was also used in Geoforma to present a more 'satisfactory' landscape. This is felt to be within the bounds of the statistical variance identified by the parametric analyses.

More specifically, the *modus operandi* for synthesising terrain based loosely on the granite areas of South West England is described below. A map of the study area is shown in Figure (6.1). No man-made features are synthesised: this is a purely physical landscape exercise.

1. An area of South West England is selected and factors such as the appropriate map scale and grid resolution are decided upon. The general characteristics of the selected topography of this area are then collected using the Vicksburg-Natick method, thereby creating a primitive surface. Alternatively a prepared primitive can be used, based on manual input.

2. Process-response models are used to establish a drainage pattern, and a special subroutine has been produced to account for the tors, based on Linton's work. It should be pointed out that Palmer and

Neilson (1962) disagreed with Linton on points of detail (e.g. the degree of effectiveness of periglacial action) but the author has not found any work that actively disputes Linton's theories. It is important to note that it is the ***form*** and not really the ***process*** that is of most interest to this part of the study. The algorithm for this is described in Appendix C). This modifies the primitive surface accordingly, although the tors are partially decorative features unless the fluvial programs are re-run, in which case the tors can form 'hard-points' which the rivers can avoid, thereby implicitly changing the valleys marginally in the same way as if 'hard' outcrops were placed in the path of the simulated river.

3. A map (at a recommended scale of 1:50,000) is created for the macro and meso terrain. Various 3D views are manipulated and compared with known photographs of areas in South West England. Initial validation is carried out.

4. Using the synthesised map and real 1:25,000 maps as a reference, an individual tor 'complex' is synthesised. This is done using a detailed version of the tor algorithm, plus the modelling of some detailed features associated with tors (weathering pits, fluted edges etc.). Again, a schematic of this is compared with photographs of real tors.

An exercise was carried out for Bodmin Moor with limited success, and no worthwhile illustrations were produced. Similar synthesised terrain exercises were conducted for Dartmoor, but as the region is so large it was necessary to use smaller-scale (1:100,000) maps, and this failed to produce any results worth reproducing in this thesis. There was no time or resource available to carry out a detailed synthesised terrain 'exercise' for the whole of Dartmoor - this is recommended as a possible future activity.

6.4 Background

The geological background to South West England is relatively complex, with sedimentary and metamorphic rocks surrounding distinct granite cupolae (Edmonds *et al* 1975, Charman *et al* 1996). Although the so-called Cornubian granites have been arranged into different types and have been examined in great detail (Exley and Stone 1964, Salmon and Powell 1998, Exley 1996), their exact geological composition and structure is of interest mainly in terms of some of the basic features. The Lundy granites are newer and different again (Dollar 1941), but once more the familiar tor and rock field landforms are to be found on Lundy - perhaps slightly different to the trained eye - but nevertheless similar. It is the granite that gives the uplands of South West England (with the exception of Exmoor) their characteristic 'postcard' appearance, and indeed the area has long been used as a region for tourism and military exercises: both 'industries' which have or could use synthesised terrain data profitably (e.g. for planning, landscape management, environmental impact of afforestation and quarrying etc.).

The following paragraphs are relevant to the modelling in that they help set the scene for the exercises involving synthesised terrain. First, upland and coastal granite regions have a certain rugged and singular beauty; Dartmoor itself is a National Park; the boundaries of which correspond fairly closely to the granite outcrop boundary. Some of the summits in Dartmoor reach nearly two thousand feet (685 m OD) and much of the area was once forested (Hoskins 1970). South West England is supposed not to have been glaciated beyond the north coast of the peninsula (Mitchell 1968). From the perspective of the human impact on the area, the landscapes have seen various stages from Palaeolithic, Neolithic and Iron Age settlements and agriculture, Industrial Era ore extraction, afforestation and deforestation, reservoir capture, quarrying and military firing ranges. Despite this generally interesting landscape and environmental development, it is the modern landscape of upland and coastal granite areas in South West England that concern this chapter.

Indeed, the physical geography and the distinctive granite landscapes of South West England are well documented (Shorter 1957, Hosking and Shrimpton 1964, Shorter *et al* 1969 and many others). Particular interest has been paid to the tors with their sometimes strange accompanying rock formations - this is of singular importance to attempts at modelling synthetic tor forms and 'micro-level' features. Such rock features on Dartmoor have been recorded as early as 1291 (Crossing 1912), and their singular topography was also recorded by early workers such as Leland (1534), Norden (1585), Carew (1602), Speed (1611) and Heath (1750). A great deal of early work was done by William Borlase, who reported on basin-like features in the Isles of Scilly (1753, 1756) and mainland Cornwall (1758), who put forward various curious origins for the features he found (e.g. 'Druidical basins'). Interestingly, several of these workers have observed that the vertical joints (what later became known as the Q, S joints - see Cloos 1936) and the horizontal joints or pseudobedding planes (the L joints identified by Cloos 1936) coincide with the structure of unusual pot-like features (again often with unlikely anthropological explanations to account for them). Some of the early workers - the pioneers of 'natural philosophy' in the 18th and 19th centuries - also reported on the 'logan' or 'logging' stones, which are large, finely balanced blocks produced by weathering (Moore 1830, Brayley 1830). Indeed, such was the singularity of the weathered rock structures in the minds of these early naturalists that some of the early aspiring geologists disagreed among themselves as to whether they were natural features at all (Statham 1859, Murray 1859, Wilkinson 1860). Many different forms of natural origin have been postulated for the tors and the micro-features (for a detailed bibliography on weathering pits and associated micro-features, with a review of several possible alternative origins see Griffin 1977), but with the development of geomorphology into a science in the late 19th and early 20th centuries there was a general agreement that tors and their associated features were linked to weathering processes of one kind or another (Reid *et al* 1912, Linton 1955, Twidale 1971 and 1976).

The moorland landscapes of South West England have been examined by workers at a macro-scale, often with the recognition of continuous and discontinuous surfaces at distinct levels. The supposedly Pliocene seaward-dipping platform backed by a bluff at 131 m OD in West Penwith (Cornwall) is well-known and has been documented by Reid (1890) and others, and more recently has been discussed by Goode and Wilson (1976). Gullick (1936) recognised surfaces at heights of 55 m OD, 122 m OD, 183 m OD and 229 m OD in Cornwall, and Balchin (1964) also recognised a generalised break in slope at 122 m OD. These surfaces are potentially useful in an attempt to construct macro-level synthesised terrain landscapes, and although they were not used in any exercises due to resource and time constraints, it would have been instructive to start with a multiple surface 'primitive' over which process-response models could have superimposed rivers and coastline.

The 131m OD platform feature, incidentally, also forms part of one of the earliest illustrations of true perspective 3D view of an OS-derived DEM in a scientific journal (Griffin and Gilmour 1981), which shows a computer view of the entire West Penwith peninsula from a simulated altitude of 30 km. Interestingly, similar views of South West England are still being shown in the same 'learned journal' via remote sensing, demonstrating that technology moves on (Smithurst 1990).

6.5 Aims and objectives

It is helpful to have some 'terms of general reference' otherwise the exercise on granite could become 'unbalanced' - it could be (on the one hand) over-simplistic and self-defeating, or it could be (on the other hand) somewhat over-complex and futile. Potential opponents of terrain synthesis may argue that one might as well use real terrain if a certain level of cost or effort is reached, and indeed, apart from the philosophical need to examine 'synthesised *versus* real', they might well be correct as far as any practical advantages are concerned.

Like the coastline exercise in the next chapter, some guidelines were laid down for the approach and the consequent aims and objectives. These are as follows:

- To reproduce certain 'classic' textbook granitic landscape areas and landforms.

- To allow composite (compound) or multi-phase landscapes or features

- To incorporate a certain stochastic element by means of fractals or other methods

- To aim at relative simplicity and speed of operation

- To achieve the usual 'good practice' for producing algorithms for integrated software suites (good performance, resilience, robustness, clarity, good documentation, accuracy etc.).

A selection of maps from the study area was purchased for the exercise. No existing DTMs or DEMs were used, and no UK OS material was involved following an unofficial warning from the OS. The 'raw material' comprised some air photographs and cartographic documentation, which is referenced as necessary.

6.5.1 Terrain Scales

A terrain synthesis exercise for the macro-terrain was carried out, followed by exercises for the medium-scale (or meso terrain) and micro features. This was done entirely independently of other work, but it is interesting to note that Waters (1964) and Small (1990) mention three surfaces in the case of Dartmoor - an 'upland surface' at about 500 m (OD) with a local relief of about 70 m; a middle surface at about 300 - 400 m (OD) and a surface around the periphery of Dartmoor consisting of planation remnants at about 250 - 300m OD.

6.5.2 Micro Terrain

(a) General

A terrain synthesis exercise for the micro-terrain was conducted, concentrating on the tor and boulder-field complex as an 'assemblage'. In this case, the macro-terrain was again used as the foundation, but the synthesised tors (which are not detailed at the macro and even the meso levels where they can be just 'dots' on the map) are modified or 'worked on', to produce some of the familiar and interesting features, including:

- Weathering pits
- Weathering pit systems (multiple pits interconnected by channels etc.)

- Troughs and similar forms
- Runnels (demonstrably draining rainwater from the tor surface)
- Fluted vertical surfaces
- Piles of boulders/jointed bedrock
- Large, medium and small isolated boulders
- Boulder fields
- Lenticular blocks stacked on the tor bedrock

The aerial photographs (Figures 6.2 and 6.3 - source unknown) show the complex boulder fields around Carn Galver (west of Zennor in West Penwith, Cornwall), looking SSW and North respectively. This tor, (or outcrop) is surrounded by a major blockfield, as the granite boulders can retain a relatively massive aspect even after extensive weathering and separation from the 'parent outcrop'. Indeed, some of the 'offshoot' boulders can be impressive in themselves, and some are several metres in diameter. The photographs are included to demonstrate the complexity and near 'randomness' of attempting to model complex landscapes in detail. However, Figures 6.4 (a and b) illustrate that some tors (in the same area) can be relatively simple landforms, with the distant hills marking the 'macro' topography of the extreme west of Cornwall. The boulders and the micro-forms have been studied in detail by the author (Griffin 1977) and therefore some considerable effort has been expended in trying to simulate them by examining existing documentation of their form and development process or processes. Interestingly, recent work by Gerrard and Ehlen (1999) examines the fractal implications of joint spacing and landform features on the Dartmoor granite. Gerrard and Ehlen found that there was a good correlation, using the fractal dimension, between micro-

Figure 6.2 View of Carn Galver tor complex, West Penwith and extensive boulder field (view looking SSW)

Figure 6.3 View of Carn Galver tor complex, West Penwith from the north

features up to the tor/landscape level, citing fractal dimensions of D = 1.43 to 1.58. Unfortunately this information was published too late for inclusion in any of the algorithms, although the implication of self-similarity is interesting, if perhaps the sample was relatively small (no of rock pavements studied = 15, compared with the sample of 1000+ sites in Griffin (1977))

(b) Modelling visualisation of rhomboidal granite boulders as 'cuboids'

One line of original research involved the positioning of a cube. This was inspired by computer graphics - the author wanted to examine the limitations on viewing a cube (where the cube could be a rhomboidal boulder in this case - or later on in this thesis it could be a house). It was found that the following properties hold true (when the cube is seen from a fixed viewpoint and rotated about its axes):

- Only 4, 7 or 9 edges can be in view at any time
- There can only be a maximum of 3 faces in view at any one time
- The side on case is critical (e.g. seeing a cube edge on has to be allowed for as a 'special case' in the programming)
- One assumes that the basal surface will always be touching the ground - this makes 'viewing' the cuboid easier.

6.6 Tor algorithm

6.6.1 General

This involved the preparation of a primitive for sweeping (e.g.1000 x 1000 grid points in a Cartesian (x,y,z) co-ordinate system). It should be noted that once again, the Cartesian (x,y,z) system adopted by the military was used, with the x-axis corresponding to the north-south,

Figure 6.4 Views of landscape near Zennor, West Penwith, Cornwall, showing simpler tor forms and distant surfaces (looking north)

the y-axis to the east-west and z (or -z) the vertical axis. This was because of the need to integrate this 'right-handed' axis set with navigation algorithms and other military models, and is standard practice in MOD and DOD projects - see Blakelock (1965) and Britting (1974) - and also see chapter three.

Granite attributes have been applied by one of several methods:

- Controlled random
- Prepared (based on classification or modelled on known area)
- Manual set-up

It should be stressed that the structures should be relatively 'realistic' or at least possible, with the idea being to simulate the construction of areas of massive granite (for tor growth and areas of high ground) and in turn simulate higher joint frequency areas for softer rocks (for lower areas or possible valleys).

6.6.2 Algorithm outline

This algorithm is designed to model the tor forms in detail, and should not be confused with the positional algorithm (which simply places tors on an existing landscape) which is explained in Appendix C. The detailed algorithm is outlined as follows:

Sweep x - y increment -1 across grid

Test for attribute granite fabric (1,2,3,4) and P-joint frequency (1,2,3,4)

Where 2 = massive, no weathering

1 = some degradation

-3 = average degradation

-4 = granite is crumbling to growan

Where 2 = no joints

1 = some joints

-3 = average joints

-4 = high frequency of joints

Drop or raise landscape surface Fabricx * Jfreq * control_delta (latter variable has the effect of raising massive/low frequency areas and dropping degraded high joint frequency areas. Control_delta is applied to attain 'correct' tuning and may need adjustment over several test runs).

Fabric = fabric_measure * attribute

Jfreq = joint_frequency * attribute

New_height = fabric + existing height * delta

Check new height against adjacent points:

North and South : [(x-1, y), (x+1, y), (x, y -1), (x, y +1)]

Diagonals: [(x-1, y-1), (x+1, y+1), (x+1, y -1), (x-1, y +1)]

and if discrepancy > set_percentage_height then adjust height drop/raise relative to mean of 4 points. This ensures relative smoothness in relation to adjacent points but still allows for small cliffs and boulders. A simple formula was calculated (by exercising basic Cartesian geometry principles) and used to plot new positions in a 2D (Cartesian X,Y) plane, where +X is 'north' and +Y is 'east' from an origin (0,0) :

Cos (Theta) + ***d*** = New X position

Sin (Theta) + d = New Y position

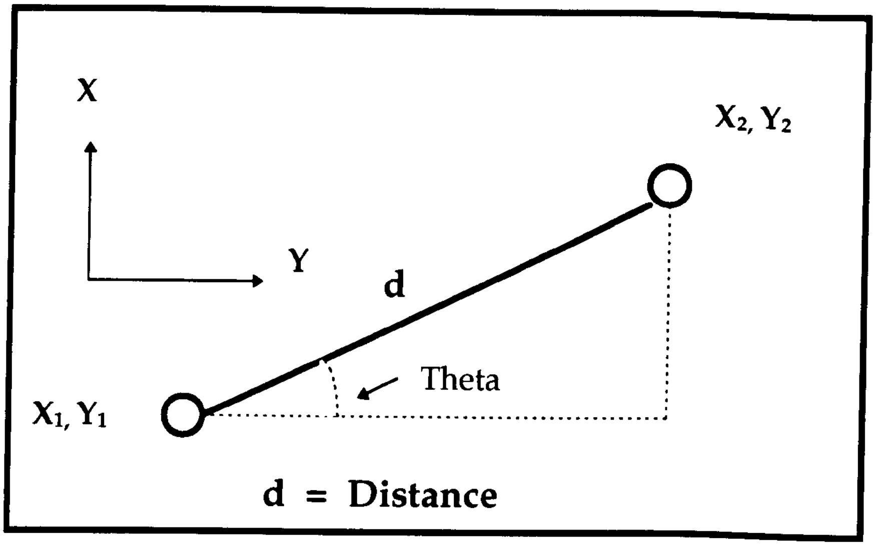


Figure 6.5 Explanation of movement across 2D surface computation

Where Theta is the angle from the old **(X_1,Y_1)** position measured to the new **(X_2,Y_2)** position on the map .

Interestingly this derivation works for 0 to 360 degrees, including solutions for both azimuth values of 0 and 360 (which are of course, equivalent). This is mentioned as many geometrical solutions involving zero and trigonometric functions cause problems at computational level (the 'zero division' problem is well known and will cause a fatal error in most programming languages).

The distance from the old position to the new position is represented by the symbol ***d*** (See 6.5).

At end of surface sweep, store new derived surface, plot (2D and 3D).

If desired: Apply auto-tests (sweep for maximum and minimum points, test against setpoint summit/lowest points allowed etc.)

6.6.3 River Valley Algorithm rationalisation

This part of the algorithm was designed to apply a river algorithm to rationalise valleys, where a slight tilt to the primitive surface (if applied) avoids many problems (such as unnecessary iteration) and tended to give the best 'Dartmoor-like' or 'Bodmin Moor-like' results. Each attempt was run and shown in 3D for assessment.

Each exercise was stored and labelled under the appropriate surface heading (or reference number) in DTED format, using a configuration control/version system for later use. Configuration control is the method by which versions and different copies can be managed and tracked - usually it takes the form of a software tool sometimes attached to a database. Good configuration control tools will 'lock' particular versions while one particular user is operating on them to save unauthorised or multiple alterations (a similar theory is applied to databases in the form of row-locking (Date 1990)).

6.7 Results

6.7.1 Relative inability to produce satisfactory meso-scale terrain

The results of the exercises are shown in Figure 6.6 where macro terrain is shown, and in Figure 6.7, where tors have been emplaced on a valley (effectively this is 'meso-terrain'). Both exercises are discussed below.

Empirical observations and numerous exercises produced some good examples of 'typical' realistic moorland-granite upland terrain (when compared with the tor landscape photographs), although there were also some failures. The failure rate (where the terrain was completely unacceptable) was about 1 in 7, and the average time to create (not present) the finished terrain was about 3 hours.

One decision that was made - reluctantly - was that the meso-terrain exercises were deemed to be relatively unsuccessful without

Figure 6. 6 Simulated area in North Bodmin Moor (Exercise 1)

inordinate manual input. This was because of several observed and suggested reasons:

- It was observed that the terrain models created tended to 'veer' towards macro-terrain or micro-terrain, and it was difficult to capture what could be described as 'meso scale terrain' without imposing manual edits (which would seem to defeat the object of applying geomorphologically-sensible methods).

- It is suggested that the maps used and the (subconscious?) input by the operators may have influenced the results

This leads one to suspect that in the context of granite scenery in South West England meso terrain is difficult to apply and that it does not produce 'good' results as far as synthesised terrain is concerned. The corollary of this is that if terrain is desired at the scales that equate to meso terrain then they should be derived from 'zooming' macro-terrain by means of interpolation or map magnification, if this can be achieved 'realistically'.

To summarise, with the techniques and algorithms described, the author produced viable macro and micro-terrain, but not terrain at a medium or meso scale. The result of this is that this particular exercise was abandoned after several unsuccessful attempts. Although it was felt that additional software could have been written to help the process, this was in turn deduced to be expensive in terms of resources; it is perhaps more honest to admit that some terrain, at some scales, defies the 'generic' approach allowed by Geoforma and the methods of preparation. This may not be true for different regions, nor is it suggested that meso terrain cannot be formed as a general rule; it may be partly a function of the landscape being analysed. For example, if the landscape comprises a 'macro' scale of drainage basins and watersheds with summit and valley-side tors, then there may not actually 'be' a meso terrain to create - it is simply - as has been suggested above - a 'magnified version' of the macro-scale. So 'meso' may be a non-existent or at least difficult to recognise category, at least in the context of synthesised terrain. Thus the classification of 'macro', meso' and 'micro' may be a false assumption. In a different area of the world, where different landform groups exist, meso-scale terrain may be quite 'legitimate' and may be detected and synthesised successfully. Indeed, there may be several scales not just 2 or 3, in other areas (see chapter 2 for some proposed scales of landforms).

6.7.2 Macro terrain

An early attempt at modelling terrain based very roughly on parameters associated with West Cornwall is found in Griffin 1987 although this is not mentioned in the original paper, which sought realism. However, it dates from the period of manual collection of DTMs from West Cornwall (Griffin and Gilmour 1981) and although it is not presented as synthesised terrain, it was an early attempt to produce 3D views for geomorphological purposes (interestingly, the author introduced a random elevation program to the data in order to try and produce synthesised terrain samples, although no records of this were kept. It does perhaps represent the author's first attempts at realising the usefulness of employing synthesised terrain models).

The three recognised surfaces on Dartmoor (Waters 1964, Small 1990) have been mentioned, and although manual trend surface analysis carried out by the author gave some tentative support to the existence of these surfaces, none were reproduced by Geoforma, with the possible exception of the 400 - 500 m OD 'surface' - which may simply just coincide with the plateau level of the area. There is no evidence for the three planation surfaces therefore by means of Geoforma execution. However, this does not in any way repudiate the existence of such surfaces since the scale at which the macro-terrain physiographic parameters were sampled (1:100,000) would probably have 'missed' them. Also, one must recall that synthesised terrain is being created, and not - strictly speaking - a map facsimile of Dartmoor.

The cross section across the macro terrain shows that the algorithm has been set up to produce tor-like structures at points where there is relatively massive granite and with a paucity of vertical (Q and S) joints, according to conventional wisdom (e.g. Linton 1955). This is simple cause and effect, but in spite of the way the primitive was set up to produce such results, it is still tempting to comment on how easily and conveniently the exercise created the expected landscape.

First, some older DTMs of Bodmin Moor were used. Figure 6.7 shows a granitic Moor-like valley created using a first-cut (i.e. very rapid) parametric analysis to produce Bodmin Moor valleys with tors. A x 2 vertical exaggeration has been introduced for effect only. The exercise was completed using the author's version of the software (i.e. it does not use Geoforma apart from a derivation of the GUI system) but it is a genuine and relatively successful attempt to create valley side and summit tors on 'Bodmin-Moor type terrain'.

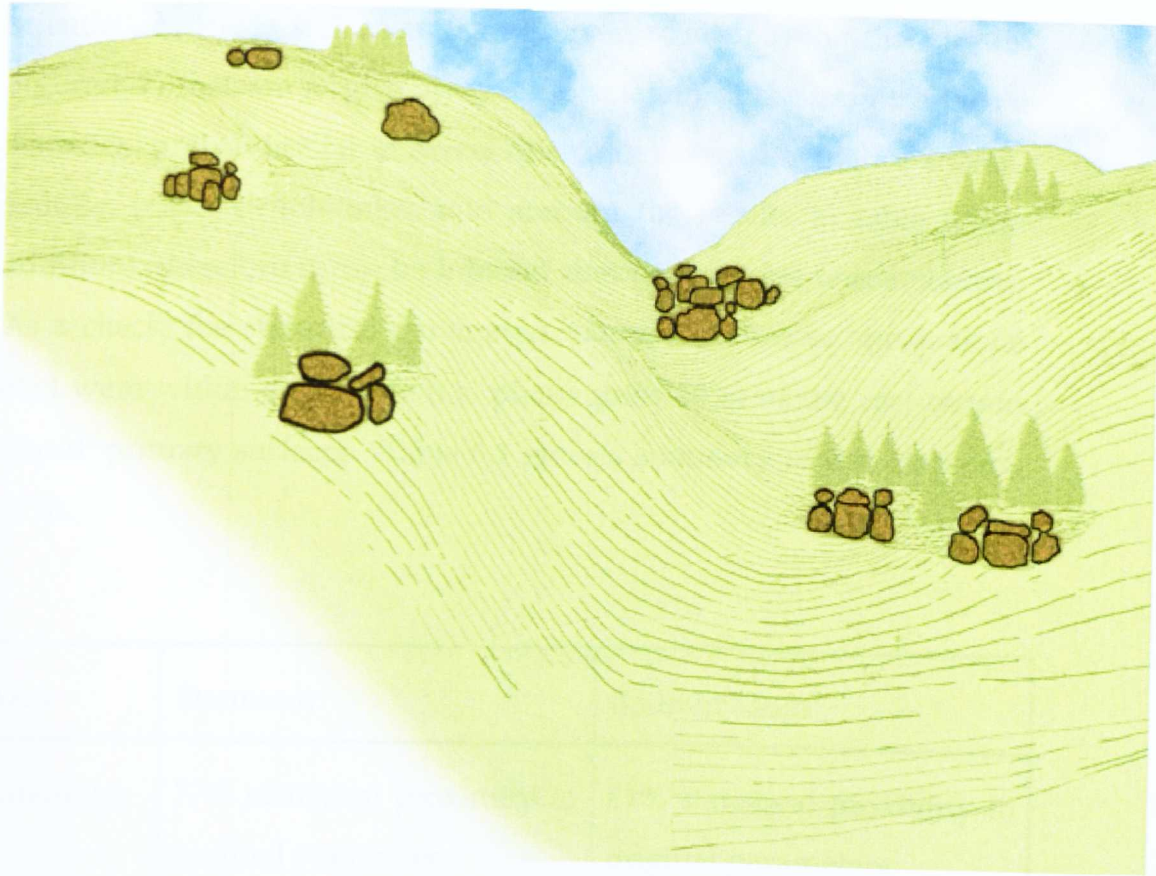


Figure 6.7 Synthesised terrain using meso-terrain and simulated tors

However, relatively few summit tors were produced, and some modification to the algorithm would have been made to correct this had time permitted. Following on from this, the 'Postcard' type views shown in Figures 6.6 and 6.7 are felt to be satisfactory. When shown to a sample of 20 people - as an 'unofficial' validation exercise carried out before the thesis was properly underway - only 2 out of the sample of 20 (5%) said that they did not think - or were not sure - that the scenery represented 'typical' Bodmin Moor). The sample had no connection with the project but they claimed to be familiar with Bodmin Moor scenery, and as such the results are satisfying in that so few failed to recognise the area (given a list of five possible areas: Snowdon/Bodmin Moor or Dartmoor/Brecon Beacons/Peak District/Cairngorms). This may be a factor of familiarity with 'recreational' scenery rather than 'seeing with the eye of an earth scientist', but it is still encouraging. Even so, it may be the tors (in Figure 6.7) that are a 'give-away'. Correlation of the results gives a statistical probability far in excess of chance even allowing for a small sample, (r = 87: this takes into account the results in table 6.1 in addition), therefore it can be inferred that the exercise was a success. As a check, the statistical parameters (summit distances, mean slope etc.) were within acceptable (i.e. plus/minus 10%) of the real terrain 'input' primary surfaces. Table 6.1 gives a summary of this closeness of fit.

Area	Dartmoor	Bodmin Moor
Attempt 1	77% statistical proximity to original parameters	81% statistical proximity to original parameters
Attempt 2	79% statistical proximity to original parameters	84% statistical proximity to original parameters

Table 6.1 Closeness of fit to inspected relief features (slope max/mean/min; distance between peaks, average summit height etc.) to synthesised terrain : Dartmoor and Bodmin Moor (note: only Bodmin Moor is shown in the figures).

6.7.3 Micro-terrain

This type of terrain is more difficult to create with true objectivity, and the tilting of individual boulders of 2 or 3 metres in diameter is hard to model with any 'realism'. A significant result of these exercises was that the operator appeared constantly to be compelled to 'interfere' and produce micro-forms (by editing) according to his or her observations in the study area. Indeed there is a symmetry and structure about the granite tors that is difficult to simulate, and it is almost easier to 'sketch' some forms freehand. This has been done using the tor algorithm outlined above but sketching the results by hand - the synthesised terrain micro features are therefore an impression (based on the algorithm) and it was not thought to be a valid use of time to model the forms using computer graphics (though this could have been done quite easily had time and resources permitted).

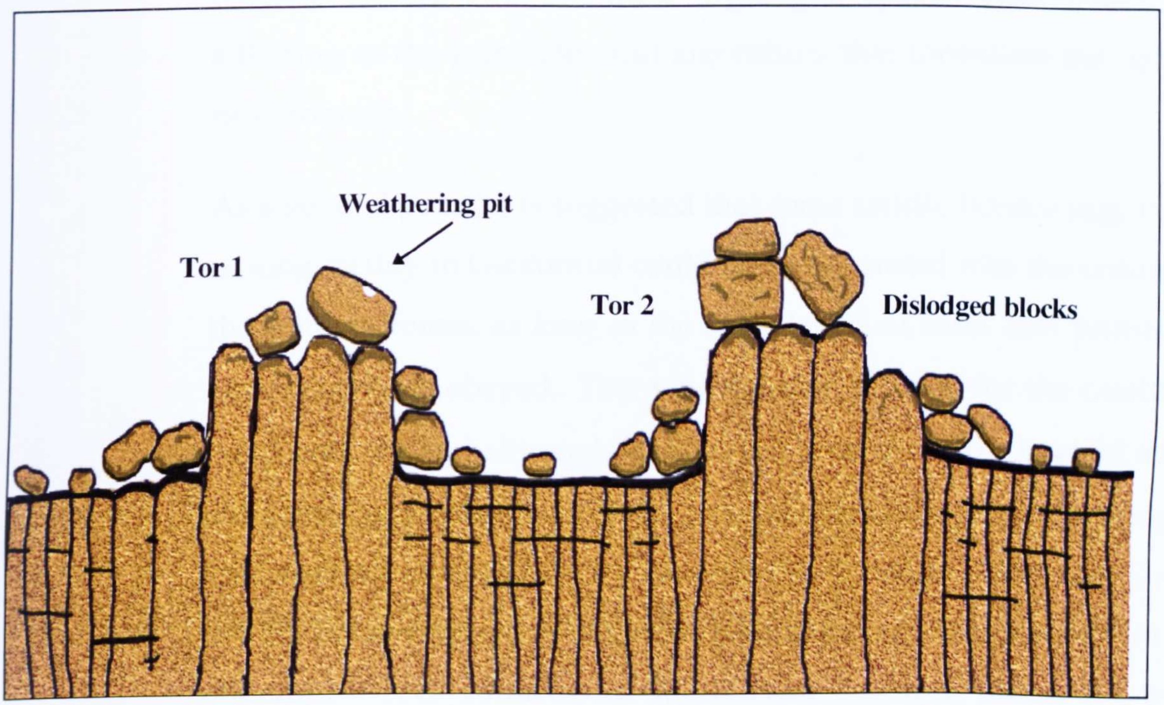


Figure 6.8 Tors based on detailed tor algorithm (sketched). Note weathering pit and dislodged block.

However, the micro-scale features have been formed by the known processes of relic and recent weathering (the distinction is hard to define), and there are a number of distinct relationships between structure and process (whether active or relic) that give these features their characteristics. Interestingly, while it is not enough for true objectivity to sketch such landforms 'freehand', this can almost be done given the largely 'constrained random' distribution of boulders, weathering pits and so-on. The boulders surrounding some of the tors form no obvious pattern, except that they are adjacent to the main outcrop where they originated. In the Luxulyan area this relationship is difficult to model, as large isolated boulders appear in woodland. Possibly they are the visible remnants of outcrops and some boulders are buried by soil and vegetation; indeed this is certainly the case in some of the areas visited in the field. This makes such boulder fields hard to model; one is almost arguing a special case rather than adhering to the principles and algorithms that formulate the 'general case' tors etc.

As a general point, it is suggested that some artistic licence (e.g. via the editing facility in Geoforma) could be incorporated into the creation of these micro forms, as long as the basic tenets of form and process are understood and obeyed. There is a general 'rule set' for the creation of these features, and although this has not been encoded, it could still be used as an algorithm if desired. The rules (actually general principles) are based on observations by Twidale (1976), Ollier (1969) and Griffin (1977). For example, one never finds weathering pits upside down (i.e. underneath rock surfaces) in South West England, unless the block itself has been inverted by falling off the tor complex.

Similarly, there are well-established relationships between the rock structure and the micro-forms. To examine this, it is seen that in an earlier work, the author established that weathering pits, boulder stacks, rock outcrop forms and other features attributed to contemporary and/or relic (possibly subsurface) weathering are intimately linked to the slope of the joints at a particular tor location (Griffin 1977, Griffin 1979). Thus the tor at Stowes' Hill (OS 1:25,000 Grid reference **SX 257725**) and Carbilly tor (or The Cheesewring, OS 1:25,000 Grid reference **SX 125754**) both on Bodmin Moor have remarkably horizontal surfaces; the weathering pits are consequently round (as elongation tends to be associated with the long axis running parallel to the slope of the rock surface). Indeed, some tors have an almost 'artificial' feel of stones placed upon one another (see Showery Tor, Bodmin Moor, OS 1:25,000 Grid reference SX 148813). Models of these tors (Fig 6.7 and 6.8) have not included the weathering pits and small features (except as manually added decorative features: see Figure 6.8), which are perhaps too small to warrant major formation algorithms, but similar structures are created at the level of the boulders and massive outcrop forms that comprise the tor.

At tor sites where there is a degree of general slope - caused by weathering exploitation of slightly-dipping (pseudobedding or L) joints reaching a maximum of 20 degrees or more - weathering pits tend to be elongated and sometimes interesting trough-like forms have been created by rain runoff, probably in comparatively recent times (e.g. post-Flandrian) - see Griffin (1977) where a hardware model has been developed to account for this elongation. A good example on Bodmin Moor is found at Elephant Rock (OS 1:25,000 Grid reference **SX 196791**), where several weathering pits have coalesced to form a trough-like feature.

For the sake of rigour, non-weathering origins were examined in Griffin (1977) to take account of all (sloping and non-sloping) weathering pits and other micro features, and these origins (which affect the morphology of other small-scale feature and not just weathering pits) were reviewed for possible inclusion into the 'micro' algorithm. A possible subglacial origin for these forms has therefore been investigated (Griffin 1977) based on fieldwork in glaciated areas of Norway and Sweden, reference to workers involved with subglacial erosional features (Gjessing 1966, 1967, Dahl 1965, 1966, 1967) and comparison with hydrodynamically-derived potholes in rivers and coastal areas (Wentworth 1944, Allen 1971, Embleton and King 1968 and Bird 1970). This is not so unlikely as it may seem, after all, absurd theories have been entertained for centuries: many pit-like forms were ascribed to 'Druids collecting blood during ritualistic sacrifices' by early workers (Borlase 1758) and even when most workers ascribed the forms to natural causes the occasional 'Druidic' theory was postulated (Burnard 1896). Indeed, it seems the tors and their micro-forms have always had a sinister fascination to some, and reports are still to be found in relatively modern times (Anon, *Daily Express* 4th October, 1926). To return to a non-weathering origin, some workers have postulated a glacial origin to explain possible erratics in South West England (Kellaway 1971). Indeed, the north coast of the Somerset-Devon-Cornwall peninsula lies close to the conventionally accepted limits of Anglian and possibly earlier ice limits (Mitchell 1960, 1968, Sugden and John 1976, Summerfield 1991, Clowes and Comfort 1998). Interestingly, erratics have been recognised in North Devon (Taylor 1956). Furthermore, there are erratic blocks and glacial drift on Lundy and in North Devon (Mitchell 1960, 1968), and the famous Porthleven coastal erratic in ***South*** Cornwall is in itself hard to explain given the conventional map of maximum ice expansion (see Sugden and John (1976)).

It is perhaps disappointing to refute such potentially exciting theories as ice covering Dartmoor, but the 'conventional' view holds, and the information about the tors and their micro-form assemblages of South West England suggest that weathering alone has been responsible for their formation (Griffin 1977). Moreover, it was weathering processes that were simulated to produce algorithms that in turn modelled micro forms. This is 'weathering' in a broad sense - either relic or surface, contemporary or subsurface - and possibly a combination of them all (Ollier 1969). A simulated 'sloping' tor form is shown as part of Figure 6.8. Again a fair degree of realism is attained, although one must draw a line as to how useful such detailed modelling is to the users listed earlier in this thesis.

Why bother with such small features? It is probably stretching the whole concept of synthesised terrain when small features measured only in a few metres are created - nevertheless the exercise was carried through to provide the completed, rounded view that was sought when the exercise requirements were formulated (in the form of 'macro', 'meso' and 'micro' terrain). Another point is that synthesis of such small features needs a good geomorphological basis on which to write algorithms; if the genesis of boulders, pit-like forms and small-scale features can generate so much literature and potential controversy, then the synthesis of the form (and not the process) is the only sensible way forward to the synthetic terrain modeller.

Finally, the Tertiary granite landscapes of Lundy Island have not been recreated, mainly because there are no significant differences in formation of structure, although the weathering pits are shallower than the Cornubian granites (by about 50%) and some of the tors lack the distinctive 'tower' structures that give the name to these interesting features (Griffin 1977). Visitors to Lundy will be familiar with some aspects of the landscape - the lack of soil cover on this exposed, wind-swept island is associated with rocky pavements, and the island is thought to have been glaciated (Mitchell 1968), although there is no evidence for this in the form and orientation of the weathering pits (Griffin 1977, 1979). It is postulated that an 'imaginary Lundy' could be synthesised quite easily, especially as there is no significant modern drainage system, apart from a small brook at the southern end of the island.

6.8 Conclusion of chapter

The work applied the upland synthesised terrain methods to a specific area, namely to the granite areas of South West England, partly as a validation exercise and partly because the author was familiar with the area and therefore more likely to observe discrepancies or successful synthesised terrain models. The following observations form a broad conclusion to this stimulating exercise:

- The production of recognisable tor and valley forms (thereby synthesising Bodmin Moor or Dartmoor) appeared to be successful.

- Planation surfaces were not reproduced in the synthesised terrain exercises of Dartmoor and Bodmin Moor, but this is probably due to the resolution and scale used as input rather than any other reason.

- Micro terrain forms were modelled but there are few 'generic' types apart from rhomboidal boulders and weathering pits, which may be too small to be worth synthesising for any practical purposes. As a result a sketch, rather than a computer rendering, is used.

- Macro and micro terrain could be recognised 'meso' terrain is more difficult to synthesise - it either does not exist or cannot be successfully modelled using the techniques available. This is interesting as Evans and Cox (1999) mention 'meso' relief in their paper in landform evolution. Having said this, a meso-terrain valley is synthesised successfully (Figure 6.7), but only perhaps because it was part of a larger AOR and is really a 'fragment of synthesised macro-terrain'. The real issue may therefore be that the scales should have been produced or indicated by the analysis, and not decided in advance of the exercise.

- It would have been interesting to have used the surfaces recognised by several workers, especially as this ties in with some of the original work done by the author (see Griffin 1987) but resources and time limitations made this impossible. A future exercise covering Dartmoor (as well as Bodmin Moor, the Land's End pluton or even non-granite uplands like Exmoor) in more detail and taking more note of the physiographic parameters would be most edifying.

- The lack of time and resources prevented a major piece of work but enough research was carried out (albeit sporadically over 10 years) to justify the examination of parts of South West England in a synthesised terrain simulation.

- Recent work examining the fractal self-similarity of landforms and granite joints on Dartmoor, although not necessarily conclusive, is nevertheless interesting and would have been useful had the information been available at the time of algorithm creation.

- It is tempting to attempt to create a synthesised terrain version of Lundy, since it combines coastal scenery with granite pavements and tors. This is high on the priority list should future exercises be carried out.

To sum up. the work shows that it is possible to model 'typical' granite moorland scenery, although more detailed forms are harder to simulate. The work validates the processes expounded in previous chapters for a special or regional landscape type. Had the time and resources been available it would have been interesting to repeat the exercise in another 'control' area using a different but distinctive rock type. Two such areas suggested to the author by colleagues included the Carboniferous limestone areas in South Wales (centred around Ystradfeldte near Brecon) or in West Ireland. It is possible that both areas could have been suitable for adapting the algorithms to produce not tors and valleys but limestone escarpments, limestone pavements, gorges and other known karst features. Such exercises must await future efforts by the author or other workers in the field of synthesised terrain .

CHAPTER 7 : COASTLINE PATTERNS AND LANDFORMS

Chapter 7

Coastline Patterns and Landforms

7.0 COASTLINE SIMULATION

Coastline has been selected from the many types of landforms for treatment to produce synthesised terrain. New algorithms would be needed, and it was also appreciated that (like glaciation), coastal landforms can be classified into an interesting mix of depositional and erosional types. This work eventually caused a new algorithm to be generated - via the author's efforts - a module in Geoforma called SCISSORS (Synthesised Coastline Initialisation, Synthesis, Storage and Object Representation System) - which was built explicitly to simulate coastal terrain.

7.1 Introduction

This chapter discusses and documents the ways by which coastline can be represented by synthetic digital terrain models, following the approach or methodologies outlined in chapter three and exercised in the previous chapters - but adapting them specifically for coastlines. Additional coastal models are described in this chapter. The whole approach is - as usual - itself represented by a set of programs that form part of the Geoforma suite of software. As reported in earlier chapters - the general concept that drives this thesis involves the synthesis of 'sensible' terrain for which 'validation' is possible, mainly as an alternative to real DTMs and in situations where *realism* and not *reality* is the main requirement.

It has been pointed out that the terrain or topography must (in the most rigorous tests) be objectively (statistically) and subjectively representative both of 'real world' terrain stereotypes and terrain chosen on the 'dial-up' method from a chosen geographical area. Alternatively, the synthesised terrain may not be linked to any specific physiographic area but can be merely representative of landforms 'suites' or assemblages. This philosophy is felt to apply to areas of coastline just as much to other areas and types of scenery. As in other areas or for specific 'types' of scenery, terrain classification techniques can be used to establish and categorise coastline. Synthesising coastline, however, has several key differences from inland terrain and the following observations are important:

- On a typical UK OS map of an area of coastline, there will be an area of 'blue' representing sea. Sometimes this 'blank' area can cover a substantial percentage of the map area. For example, the OS Landranger map 123 at 1:50000, 2nd series, 1984, of the Lleyn Peninsula in North West Wales, is about 55% sea, and 45% land (including Bardsey Island). This is simply the way the map is made - the 'trend and the shape' of the Lleyn peninsula makes it difficult for the OS to portray the area in any other (more economical) way unless the sheet is not to 'key in' with the 'jigsaw' OS gridded 1:50,000 coverage of Great Britain - visible on the back of any OS 1:50,000 folded map sheet. The underwater contours (represented by Admiralty Charts and other sources of information) are not represented on typical OS maps (apart from mean high and low tidal limits), and indeed they are also beyond the scope of the terrain synthesis work in general as this area is felt to belong not to geomorphology but more to oceanography and specialised marine earth sciences (although some areas of potential synthesis are discussed as 'possible futures topics for research' in a later chapter).

- The land-sea interface - or littoral area - need careful consideration as it can vary so much in type. For example, these boundaries can range from a vertical cliff to a wide area of marshes, from mangrove swamps to temperate estuarine topography and salt marshes. Tidal range is also an important factor, rendering the landscape difficult to map unless high and low water marks are delimited.

- Bearing in mind the possible variations of coastline scenery, it is suggested that an accepted method or algorithm is clearly required to add some rigour to the definition and synthesis of such 'difficult' scenery.

- Coastlines can be a far more obtrusive facet of the earth's landscape than is appreciated. The island landmass of Great Britain alone is estimated (by cursory inspection) to have a coastline of the order of at least 3000 kilometres at a map scale of 1:500,000. Indeed according to some authorities (see for example Mandelbrot (1967), this can be increased almost exponentially, like magnifying a snowflake - if one considers the 'self-similarity effect' postulated as part of fractal mathematics: coastline is virtually infinite if one continuously enlarges the scale.

- Coastlines represent the interface between the land and the oceans of the world. Therefore 'inland' type scenery (stream systems, hills, deserts, glacial features, granite uplands and so-on) 'terminate' at the coast, often with great variety. This can be quite dramatic, in an erosional situation with high cliffs, or it can be 'damped' down by a broad band of (for example) tidal marshes or salt flats in possible submerging (non-erosive) situations. However, both extremes are to be found: the cliff coastline is as valid a candidate for potential synthesised terrain form as an estuary or a mangrove swamp.

- Finally, islands - particular island archipelagos or complex groups of hundreds of islands and islets (like the Lofoten Islands, the 'skaergaard' of southern Norway and Sweden and the Isles of Scilly) are also considered.

Therefore, a 'coastline algorithm' has been constructed which adheres to the points laid out above and which obeys the guidelines laid down indirectly by workers in the field of coastal geomorphology/geology. The algorithm is based on a carefully selected 'phased' approach involving geomorphological research and input into computer programs. Inevitably there is a manual aspect to the methodology - it would be difficult and perhaps self-defeating to attempt a wholly automatic system given the variance in coastline types. Coastline synthesis can thus be modelled by the usual suite of methods, as well as 'special' processes which are themselves represented digitally by a combination of stochastic and process-response methods.

7.2 Salient aspects of the work

7.2.1 Overview

Salient requirements for the coastal simulation were derived from what are known as 'terms of reference' (TOR). The TOR for the proposed coastline algorithm were decided on by process of trial and error and by the author writing short working papers (ref: DERA contract: NNR/25b/FY95/96) which were used to canvass the views of colleagues and learned authorities. These working papers helped contribute to this thesis.

The TOR process was then used to construct the algorithm that would help construct the eventual program module (once the architecture of all the modules was completed). The TOR or requirements for synthesised coastline terrain were expressed as follows:

> *Coastline:*
>
> *An algorithm for representing coastline characteristics for different coastal landforms will be developed and embodied into software. This will represent the coastline patterns that are representative of the geographical areas considered.*

Experience gained during the research leading to this thesis (Griffin 1987) indicated that it is good practice to make such algorithms as 'general-purpose' as possible, without compromising the main objective or drawing too heavily on any of the resources involved in their creation. For example, one of the advantages of the simulation reported in this paper was the rapidity with which it can produce reasonably realistic DEMs - an attribute appreciated and exploited independently by other authors (Eklundh and Martensson 1995).

Also, the work of other authors may be invaluable in establishing parts of the algorithm, or (as in the case of coastline) demonstrating that a detailed sophisticated <u>generic</u> model was far beyond the resources of the MOD project.

One of the reasons coastal tracts were of interest is because the geographical areas of responsibility (AOR) in use tended to be of interest to the military (due to past experience and availability of map data), typically the Persian Gulf and the defence of the UK coastline, although this changed as additional world regions were considered as operational areas for British and NATO forces. For example, there is a well-known but undocumented story at the Department of Military Survey (MOD) that the Falkland Islands were 're-mapped' at a

1:50,000 scale within a matter of days prior to the Falklands war of April 1982 - this effort involved virtually the whole staff of that establishment working round the clock (see Hastings and Jenkins (1983) for general maps of the Falklands showing salient areas with respect to the campaign of 1982). This story - communicated to the author during a visit to MOD in 1984 - need not be substantiated for the purposes of this thesis, nor does it involve synthesised terrain, but it underlines the need for accurate (and sometimes 'emergency') coastal mapping for the Royal Navy and the Royal Air Force, not just the British Army.

The story also demonstrates the effort needed for mapping even relatively small parts of the world, and the importance if a 'brushfire' war breaks out unexpectedly, as did the Falklands conflict (Hastings and Jenkins 1983). The landing site in San Carlos Water, which was only selected for operations in 1982 after careful study of the then newly revised Falkland military (OS) 1:50,000 maps and - presumably - the admiralty charts. Amphibious landing are always hazardous and this operation was no exception; the only strange feature being that the normal 3 to 1 superiority in troop numbers should belong to the attacking force (who would expect to lose more men as casualties) rather - as in this case - than the defenders (Blandford, 1999). The presence of good intelligence through maps and visits to the landing area was of prime importance to the campaign. Also, the various tactical considerations along the rugged coastline - such as intervisibility for siting anti-aircraft batteries and the capture of salient relief features were also of prime importance - all these factors are considered throughout this thesis at some stage. This is also an example where synthesised terrain is of little or no use - operational maps must reflect real areas, be accurate and have no place in the range of synthesised terrain products - this distinction must be made clear.

Naturally a war breaking out in an unexpected region would generate massive demand for maps and charts. This of course is the opposite of synthesised terrain, where accuracy and reality do not matter, but it does underline the fact that the methods are similar. Indeed, it was stated at the beginning of this thesis that synthesised terrain DTMs are stored in formats like DTED and DFAD, and are considered no different from real-world DTMs as far as processing, presentation and storage is concerned. The same applies - of course - to simulated coastal regions.

It would be useful therefore to accommodate reasonable additions to the landform inventory with the minimum of trouble, if only to move away from the military dominated choice of physiographic region and select areas of interest to the geomorphologist. Moreover, the algorithms will benefit from such in-built flexibility that would - in an ideal world, allow the coastlines of the world to be represented by means of synthetic topography.

One further design principle is to keep the algorithms as simple as possible. However, out of necessity the sheer complexity and sophistication of the systems being modelled sometimes overload the amount of detail in the algorithms; a minor disadvantage that is outweighed to some extent by the precise results and the clear layout, object-oriented design and good documentation associated with the code.

7.2.2 The role of the 'mundane' versus the 'spectacular'

Finally, the preliminary 'sorting and filtering' of landforms is a vital part of the algorithm development. This is because any cursory glance at some of the more elderly geomorphological textbooks will show the reader that such works tend to concentrate on either the singular or the exceptional landforms. This was a problem with the MOD, who were seduced by pictures in somewhat dated textbooks such as Holmes (1972) or more modern textbooks (Chorley *et al* (1985), Summerfield (1991), Renton 1994) into thinking that much of the world's coastline is highly photogenic and steep (and therefore dangerous for military operations such as amphibious landings).

Consider this observation: whole chapters in this thesis could have been devoted to comparatively rare yet interesting and well-documented glacial forms such as tors (Linton 1955) and drumlins (Chorley 1959), while the mundane, shallow-dipping river-valley basins, nondescript or undulating land and composite-facet slopes that make up most of the world's landscape are proportionally hardly represented at all, except for the standard few pages in a textbook. This does not mean that slopes and common features are not studied intensely - far from it - but is does mean that a layman skipping through a typical geomorphological textbook might get a biased view as to what is 'interesting' as opposed to what is commonplace. After all, most of the topography of South East England comprises slope facets which are related to some part of a drainage system, but there are few areas in South East England (apart from the chalk uplands and some coastal areas such as Beachy Head) where one is struck by the steepness of the slopes or the impressive nature of the relief.

Coastlines are no exception, and the textbook reader will be assailed by the atypical and the unusual, rather than the mundane and the 'usual'. A glance through the chapter on 'Coastal scenery and the work of the sea' (Holmes 1972) reinforces this; although this in no way detracts from the excellence of the work on general processes. Photographs of sea stacks, blowholes and arches abound (see also

Dury (1986), Strahler and Strahler (1987)), although these probably make up a small percentage of the world's coastline landforms. This is a question of the minority of 'exotic' features being described in greater detail than the 'mundane', even though the latter are by far in the majority - most coastlines are demonstrably not an endless line of blowholes and sea stacks but are low marshy areas, beaches, deltas, shallow clifflines etc. However 'exotic' features have certain attributes:

- By definition they are interesting - sometimes spectacular - and photogenic
- They easily demonstrate the point the textbook author is trying to make
- They have names (whereas non-descript features are just 'cliffs' even though they may exhibit thousands of variations on the theme in terms of profile, height, composition, rates of erosion etc.).

This is not being negative: the atypical and the 'freak' appear in textbooks because they describe particular coastal erosional or depositional processes so much better than the commonplace or the ordinary. Therefore considerable geomorphological forethought has been put into this chapter to ensure that the landforms being synthesised are indeed both representative and realistic, and do not represent some kind of exotic landform compendium.

7.2.3 Modelling of coastlines (Other methods)

The main text for the algorithm cited below, other than general works and Valentin's (1952) model, has been based on standard texts - e.g. Holmes (1972), Carter and Woodroffe (1997), Clowes and Comfort (1998) although the algorithm is not based on any specific model except Valentin's, which is simple and rigorous enough to be encoded into Geoforma within the time available for design and implementation. Valentin's model is relatively old and crude, but it is simple, easy to turn into an algorithm and it has not, to the author's knowledge, been discredited. Of more importance - it was requested by the MOD TOR and this gave little scope for more modern approach or more sophisticated models. This literature research work gives an insight into the Late Quaternary shoreline dynamics of several areas. Although the project does not concern itself with chronology (because the terms 'Flandrian' or indeed 'Quaternary' have no meaning to the military analysts) they are of great assistance in understanding the dynamics driving coastline evolution. They also suggest how intensely difficult it is to produce 'generic' models', apart from at a 'text book' level; hence the choice of the Valentin model *by the sponsors and not by the author.* The author also examined works such as Chorley and Kennedy (1971), Chorley, Schumm and Sugden (1985), and Roberts (1998) - for example) to check that the 'Valentin algorithm', although simplistic, is at least viable for the purposes of synthesised terrain modelling.

Some computer simulation experiments have been conducted, and the need for multidisciplinary knowledge (as stressed in this thesis too, of course) is reported by Cowell and Thom (1997). They describe forward simulation modelling as a conventional, deterministic approach used to predict the value of observable output variables for given parameters (Tarantola 1987). 'Inverse' modelling is also described by Cowell and Thom, as it tends to coincide with the 'what if' Markovian properties of Schumm (1991). Anderssen (1992) suggested that inverse simulation of coastlines and coastal evolution is necessary because the *'available data and constraints support more than one solution'.* This supports the essentially stochastic nature of morphodynamics (according to Cowell and Thom) and is cited as an engineering tool for determining different 'outcomes'. This is interesting, as it is the nearest that 'conventional' wisdom approaches synthesised terrain - although there are clearly some constraints to the boundaries of the term *synthesis*. Nevertheless, these works are encouraging, as they suggest that synthesised coastal terrain is non-trivial, and that the author is once again covering multidsciplinary, leading-edge research.

Figure 7.1 shows the results of a computer simulation (from Cowell *et al* 1992) of marine transgression in Australia. The diagram illustrates the result of marine transgression 270 km south of Sydney, Australia. The axes are scaled in metres and time increments and a total sea level rise of about 90m is recorded. These simulations are for depositional coastal areas. For rocky coasts, Griggs and Trenhaile (1997) suggest that *'Rock coasts are dynamic landscape elements that are adjusting to the contemporary morphogenic environment'*. They go on to conclude that *'We are still unable, however, to identify and quantify the erosive processes operating on rock coasts . . . mathematical modelling can be used to simulate the long-term development of rock coasts, but reliable models must also be based upon reliable field data'*.

This compounds the author's dilemma about modelling coastal terrain; there is no all-embracing simple model or algorithm; there are many types of coastal scenery in a range of climatic and physiographic examples. If we then take into account catastrophism, geology, the effects of man and other events (such as Tsunami etc.) it soon becomes clear that a simple, generic model of synthesised coastal terrain is far beyond the resources of the research project.

By way of contrast, mathematicians have been involved with coastlines, especially by using fractal self-similarity algorithms (Mandelbrot 1982). Interestingly, Mandelbrot has compared a

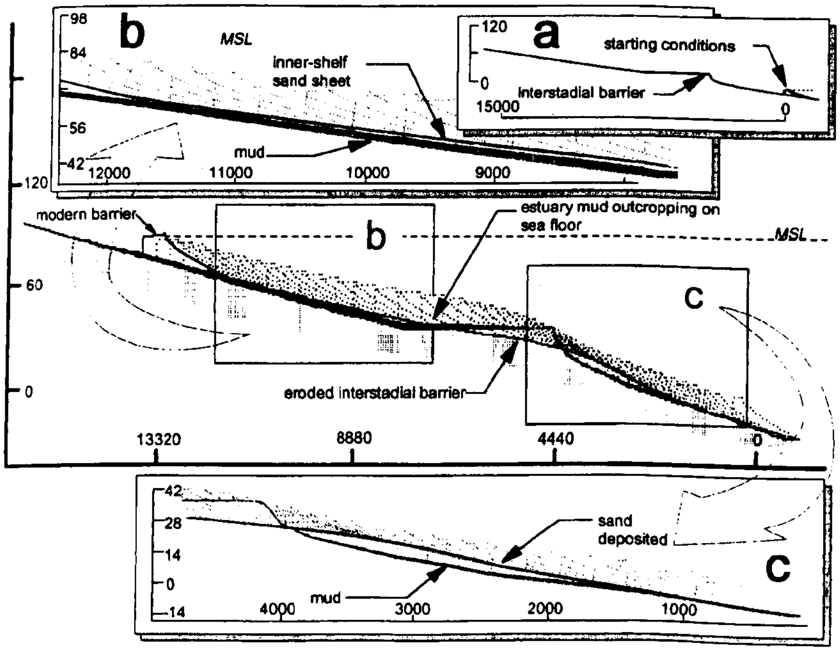


Figure 7.1 Computer simulation of marine transgression with reference to Sydney, Australia (after Cowell *et al* 1992).

coastline with a snowflake, in that each bay or creek has innumerable smaller creeks, each of which have yet smaller forms, representing a hierarchical structure which, in effect, is 'almost infinite' as it goes down from kilometres to metres to centimetres.

In the real world the application (not necessarily the existence) of such self-similarity is questionable, and although there is currently a more balanced view of such concepts as fractals, one need only compare Mandelbrot's rather sweeping statements with the careful work done on coastal evolution by Lakhan and Trenhaile (1989) - who produced a computer model - and workers such as Woodroffe *et al* 1993, who demonstrated three phases of Holocene evolution spanning nearly 3000 years (from a transgressive phase from 8000 - 6800 years BP, through a 'big swamp' phase from 6800 - 5300 years BP, to a sinuous/cuspate phase after 5300 years BP in the Northern territory, Australia (Figure 7.2).

The theme of the author's research is thought to be correct in adopting the simplest viable model available that covers all coastlines - that of Valentin - which is used as the standard 'textbook' model. It must be remembered that the TOR demand almost any type of coastline to be simulated, and although (in retrospect) this probably should have been contested and two or three 'typical' coastline models developed instead - it was adopted because of its simplicity. The general objectives and terms of reference have been laid out above. The following paragraphs build on this approach and describe in more detail some of the design aims that underpin the work on coastal landforms. The following aims were established:

- To reproduce certain 'classic' textbook coastline tracts and coastal landforms (allowing for the sensationalist viewpoint of some texts).

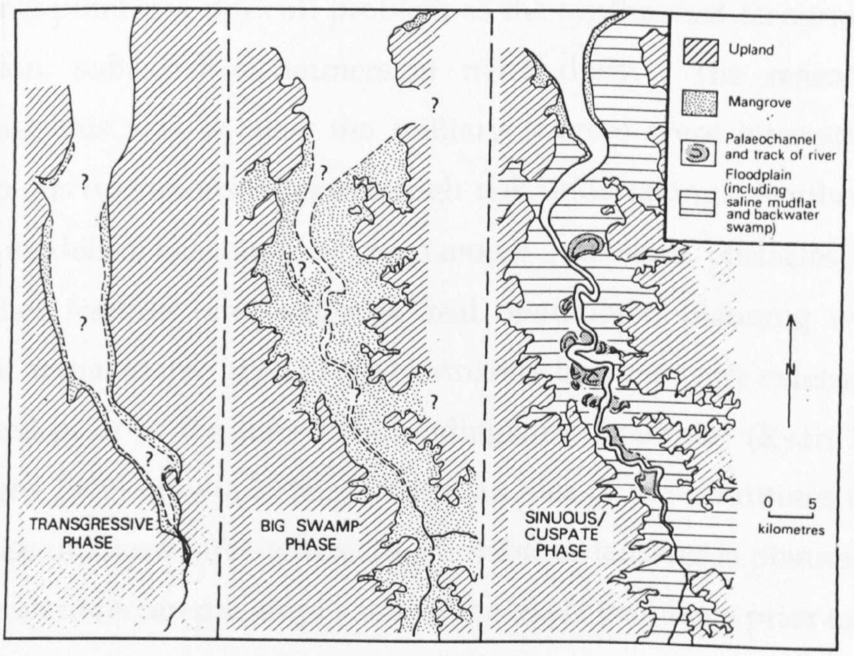


Figure 7.2 Phases of marine evolution in Northern Territories, Australia (after Woodroffe *et al* 1993).

- To allow composite (compound) or multi-phase coastlines
- To incorporate a certain stochastic element by means of fractals or other methods
- To aim at relative simplicity
- To achieve the usual good practice criteria for producing algorithms for integrated software suites (good performance, resilience, robustness, clarity, good documentation etc.).
- To achieve Littoral zone representation

This final point is a difficult problem as the synthesised terrain is, by definition, subjected to immersion twice daily. The reason for including this was because the military sources were interested in amphibious operations: always a high risk undertaking. Synthesised terrain models of beaches could help model quicksand, obstacles, reefs and other features, and although real operational planning would demand actual maps - the D-Day Normandy beaches were extensively examined prior to the June 1944 landings, for example (Ryan 1960, Blandford 1999) - it would help to gain an idea of the conditions in an otherwise unknown area where an amphibious landing is planned, so that simulations can pre-empt some of the likely problems prior to real maps arriving. It was felt that a more thorough treatment of coastal simulation and marine synthesised terrain could be carried out as a possible future exercise.

7.3 Coastline Classification

Before any attempt can be made to synthesise coastlines in general and coastal landforms in particular, some considerable effort must be directed at understanding the fundamental questions associated with them, such as:

- Why bother to synthesis coastline? Why not just terminate the landscape with a linear feature to denote the coast?

- What are the general types of coastline found in the world?

- Can these be classified into a useful taxonomy?

- Can the 'conventional wisdom' of geomorphological textbooks be harnessed for this thesis?

- How can the coastline examples be simplified such that they are of use to the thesis?

- Can the coastline tracts and coastal landforms be usefully and realistically synthesised at the map scales required by the research?

The questions are addressed and answered below, although it is stressed that the simulation work is seen as being at an early stage in the development of coastline algorithms and is not claimed to be conclusive or definitive.

Indeed the first of these questions - *why bother to develop models of coastline* - can be answered immediately. The response here is that coastline must be synthesised because landscapes generally would be incomplete without it - the level of detail already addressed is reason enough. The residents of Great Britain live on a relatively small island and coastline is by definition never far. Moreover, coastal areas have the own unique character and sets of landforms, and have generated a specialised branch in geomorphology. Indeed, some areas of the world are thought of only in terms of their coastal features - such as the Cliffs of the Atlantic coasts of Ireland, west Britain, France and Spain, the Dalmatia coast of former-Yugoslavia (Croatia), the Mississippi and Nile deltas and vast areas of mango swamps, salt marshes and tidal fenland found at different locations around the world. Indeed, for an apparent linear interface between sea and land, the coastal landforms of some areas stretch a remarkable distance inland.

As ever, the chapter and the software development that follows, are directed at satisfying the requirements of the current research. The work involves simplifying the wealth of information on coastal landforms and to some extent attempts to model 'zones' or regional stereotypes as rigorously as possible. As with most of the synthesised terrain work, there is a 'trade-off' between the idealism of very high integrity artificial terrain on the one hand, and the practical necessities of producing 'models to order' on the other. For coastlines, research into the literature showed that perhaps a well known and simple model is that first explained by Valentin (1952). This model, together with the adoption of its main concepts, is explained later in this chapter. It should be stressed that the choice of model was constrained by time and resources, and not least by the necessity of explaining the chosen model - even though it may be geomorphologically 'dated' and barely acceptable to geomorphological marine researchers - to a lay audience.

Finally, the design aims are made a little more difficult by the large body of scientific research conducted into the understanding, classification and explanation of coastal features, as this research has invariably been directed at almost any goal except synthesis. Once again the leading edge nature of the work must be underlined.

Previous studies of the coastline have centred on specific events associated with the action of the sea, such as the slope and cliff erosion and stability work conducted by engineers, surveyors and planners. Academic studies of coastline morphology and process are of key interest to this work, but this must be carefully 'filtered' as so much of this is concerned with relic features, chronology or with too much detail.

For this reason some 'classic' coastal forms such as hydrodynamic potholes (only a few metres across), sea stacks, blowholes, arches and caves cannot be modelled either because they do not appear on maps (such as cave complexes) or simply because they are too small. Similarly, the detailed genesis of a 'compound coast' affected by multiple sea level changes, glacial/interglacial and interstadial phenomena and perhaps other action such as volcanic eruption or reef development would be far too complex or would plead a special case.

7.4 Approach

This chapter, as stated earlier, examines the taxonomy of coastline features in order to provide a relatively straightforward and useful set of descriptive and statistically-based inputs to the work. The working name for the Coastline synthesis algorithm (included in Geoforma as a subprogram or module - see the Geoforma architecture in chapter three) was coined by an MOD worker as SCISSORS (Synthesised Coastline Initialisation, Synthesis, Storage and Object Representation System) - hitherto the author had referred to it as 'the coastline simulator' but the acronym had a certain absurdity so the name was retained.

The approach taken relies on the steps adopted throughout the work in this thesis, supported by the design aims outlined above. The steps are as follows:

s1 General survey of coastline types and coastal landforms paying attention to textbook literature, cartographic evidence etc.

s2 Selection of main types and sub-types s3 Classification according description criteria

s4 Establishment of 'compendium' of landforms

s5 Effect of geographical area/latitude examined

s6 Consideration of Composite forms

s7 Consideration of Relic forms

s8 Inclusion / Exclusion of special cases

s9 Effects of stochastic/process-response formation for specific cases

s10 Final production of 'look-up' table and advice on usage

s11 Final input as PLA (Plain Language Algorithm).

The final result was therefore a well-considered, balanced model of coastline and coastal landforms of use to the research and its suite of physical terrain creation programs. The work is being done in advance of specific geographical areas but the result at step s11 should be general and flexible enough for use virtually anywhere. One of the outputs of this chapter is to identify those geographical areas and coastline types that should not be modelled as they are too specialised (unless the exact area is called for, of course).

The usual method of synthesising terrain in this research project is to precede the simulation by a phase of landform classification according to the various techniques pioneered by the US Army and reported in chapter two and chapter three. The landform is then 'deconstructed' and 're-built' according to various stochastic reference criteria. In some cases a process-response model is included for extreme realism and the subsequent creation of detailed erosional and depositional landforms. This latter point is characterised by the step s9 above, which although difficult to produce algorithmically (as it has to satisfy a reasonable amount of academic cross-examination) is the final step that puts in the acute realism to the already highly-representative terrain model. It is this unlooked-for level of authenticity that differentiates the work from almost any known area of comparative research or development.

This approach is considered throughout the work on coastline features, as the outputs of this work had to accord (during one critical period) with existing practices in the MOD research project. Indeed, other ideas were introduced. Figure 7.3 shows the spatial boundaries of a typical coast from Cowell and Thom (1997) - after Inman and Brush (1973). This is included because it illustrates - on a regional scale - the different elements that can make up elements of an algorithm on synthesised coastline. Figure 7.4 is another 'text-book' model of cliff development (after Bunnett 1989), which is included to show the kind of model that can be programmed relatively easily. This can be contrasted with a photograph of a cove in West Cornwall (Figure 7.5), which shows that at a micro-level such detail would be quite beyond Valentin's model. Indeed, the tors and rock exposures along the coast would require the detailed modelling of the type expounded in the last chapter on tors (chapter 6). However, it was felt that such detail - which would be barely discernible even on a 1:25,000 OS map, is beyond the scope of the SCISSORS module (or indeed any addition unless this had a large manual or semi-manual input as explained in Appendix B).

Moreover, from a philosophical point of view, the 'finished product' is a DTM (in map, database - DTED/DFAD and 3D view output formats) and the end user (i.e. an army simulator user in this case) did not want to know about the Quaternary evolution shown in Figure 7.2

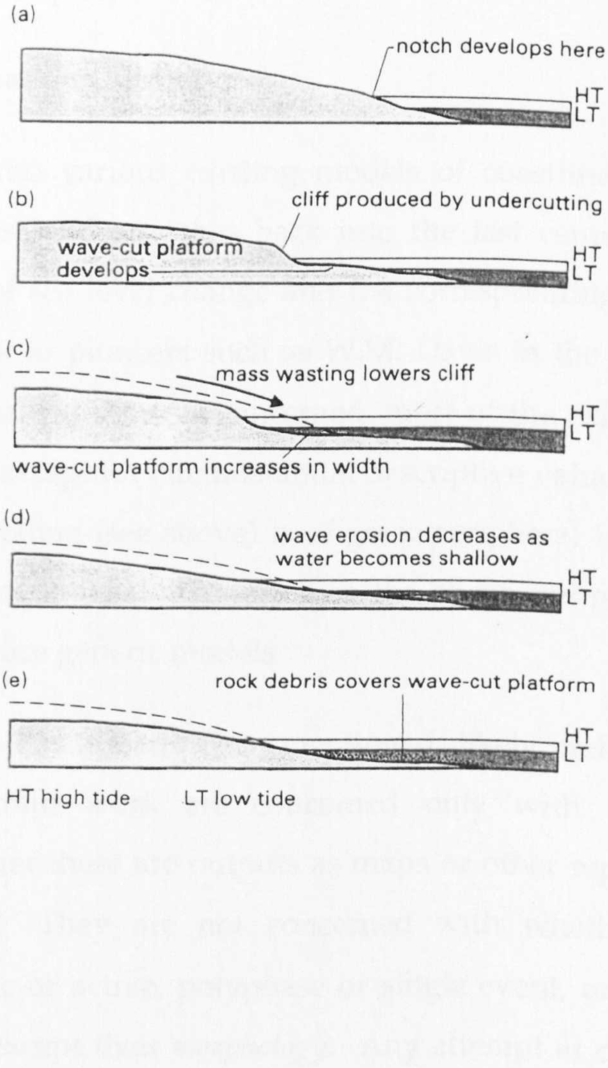


Figure 7.4 Stages in the development of a cliff and a wave-cut platform (after Bunnett 1989)

- therefore regrettably such models are really a means to an end - but at least they imbue some geomorphological credence and follow conventional geomorphological thought - even if sometimes it is at textbook 'level'. The author made it a point of honour to include as much geomorphological 'credibility' in the algorithm (and thereby implicitly in the SCISSORS module) as was possible. It was also possible for the author to write software away from the main MOD projects, and some encouraging results were produced (see later sections in this chapter).

7.5 Classification Criteria

The research into various existing models of coastline and coastal landform is vast and stretches back into the last century. Indeed, many models of sea level change and the corresponding activities of rivers date back to pioneers such as W.M. Davis in the 1890s (Davis 1896). As far as this work is concerned, most of the existing models are of little use except for circumstantial descriptive value - indeed the section on modelling (see above) is of great peripheral interest but is rather depressing in that it underlines the sheer complexity of the attempt to produce generic models.

One factor here has already been mentioned: likely end-users of the synthesised terrain work are concerned only with the finished products, whether these are outputs as maps or other representations of topography. They are not concerned with whether coastline features are relic or active, polyphase or single event, or indeed any other attribute except their *morphology*. Any attempt at classification, therefore, must take into account this overriding concern with form, and not creation, process-response or age.

Other classification criteria are useful only in that they help reach this end-product, which is expressed in terms of form or because they add

Figure 7.5 Photograph of coastal area in West Cornwall, near Lamorna. Note rock outcrops on bevelled cliffs and general level of detail. (Author's collection).

value in some other way. For example, the fact that a wave-cut platform might be partially buried by sand from ancient cliff landslides is of little interest from a geomorphological view to military users, but it yields as incidental material the fact that the geological make-up of the landform is a friable material or sand covering solid rock. If such data sets are presented to certain military users - for example - the drivers of Armoured Fighting Vehicles (AFVs) under simulation conditions - then this in turn might suggest that the likely ground pressure characteristics for the AFVs are predictable, thereby yielding a probable mobility factor given different meteorological conditions. Any military planner will stress the importance of the 'going' (ground conditions) and the weather on operations - one only need read about the tragic waste of life and the aftermath following the third battle of Ypres in 1917 (Brown 1998) because of the failure of the commanders to inspect the battlefield and understand the going conditions to realise this - see Liddel-Hart (1981) as a general reference for WWI and WWII maps and terrain explanations, as well as Goodenough's (1982) work *War Maps*. Mitchell (1991) also identifies several military examples related to ground conditions and landscape types, including one from World War I.

These examples are given partly to show the level of complexity and partly to illustrate that the main requirements are understood - the difficult process of classifying landforms is therefore justified and is deemed to repay the effort invested in it.

7.6 Survey of Coastlines and Coastal Landforms

This section is concerned with surveying the literature for types of coastline and examples of the landforms which characterise coastal areas generally. *Coastline* is defined as the stretch of terrain, from perhaps a single kilometre up to hundreds of kilometres in span, where the land meets the sea. This can be a fluvial outlet, such as an estuary, ria or fjord; a straight length of cliffs, dunes, beaches or marshland; rocky bays and islets such as the skjaergaard of western Norway, or some convoluted feature such as a mangrove swamp or ice sheet. The coastline may extend some kilometres inland, in the case of coastal dunes for example, or may be very sharp as in the case of where steep cliffs suddenly delimit the coast in parts of western England and Ireland.

Very often the coastline is characterised by a littoral zone where there is a wide tidal range, exhibited by mud flats or rocky wave-cut platforms. It must be stressed that this exercise is concerned with modern coastlines - relic coastal features such as the 'famous' 131m (430 ft) planation platform in the west of Cornwall, UK, is a distinctive feature (and was modelled in 3D by Griffin and Gilmour in 1981) but it has no bearing on the representation of coastline in this thesis. Equally, vast offshore tracts of coral reefs, mudflats, sandbanks and other intertidal (littoral) and offshore features are not represented in this study.

'Typical' coastline features are difficult to generalise, although some effort has been directed at showing cliffs and beach forms (see Figure 7.4). In reality, a list of the chapter headings in Carter and Woodroffe (1997) indicates the great diversity in the real world (e.g. Deltaic Coasts, Wave-dominated coasts, Macrotidal estuaries etc.).

Distinct from, yet part of, coastlines are the *coastal landforms*. These, quite simply, are the commonly-recognised forms associated with marine erosion and deposition (or a mixture of the two). Many of these have been dismissed already from the work on account of their scale or non-appearance on maps. Others, such as icebergs and glaciers flowing out to sea are not true landforms, are ephemeral and can be similarly discounted. Others again are so rare that they are found on picture postcards - usually these are strange-shaped stacks or other products of differential weathering. The landforms of concern to this work at the scales and levels of detail being used are typically features such as cliffs, sand dunes, beaches, wave-cut platforms, bars and others. It is the *assemblage* of landforms that make up the coastline, the one is a subset of the other. Nearly all coastlines have been initiated by relative movements between land and sea, usually either by either emergence or submergence. Emergence is associated with isostatic recovery (among other reasons), whereby submergence is usually associated with 'drowning' of the landscape to form rias or other features. Indeed, most classifications of the coastal scenery adhere to these two types, even though they are not always clear-cut. As mentioned above, Valentin (1952) proposed a useful if rather dated model for classifying coasts, which is expressed graphically in Figure 7.6.

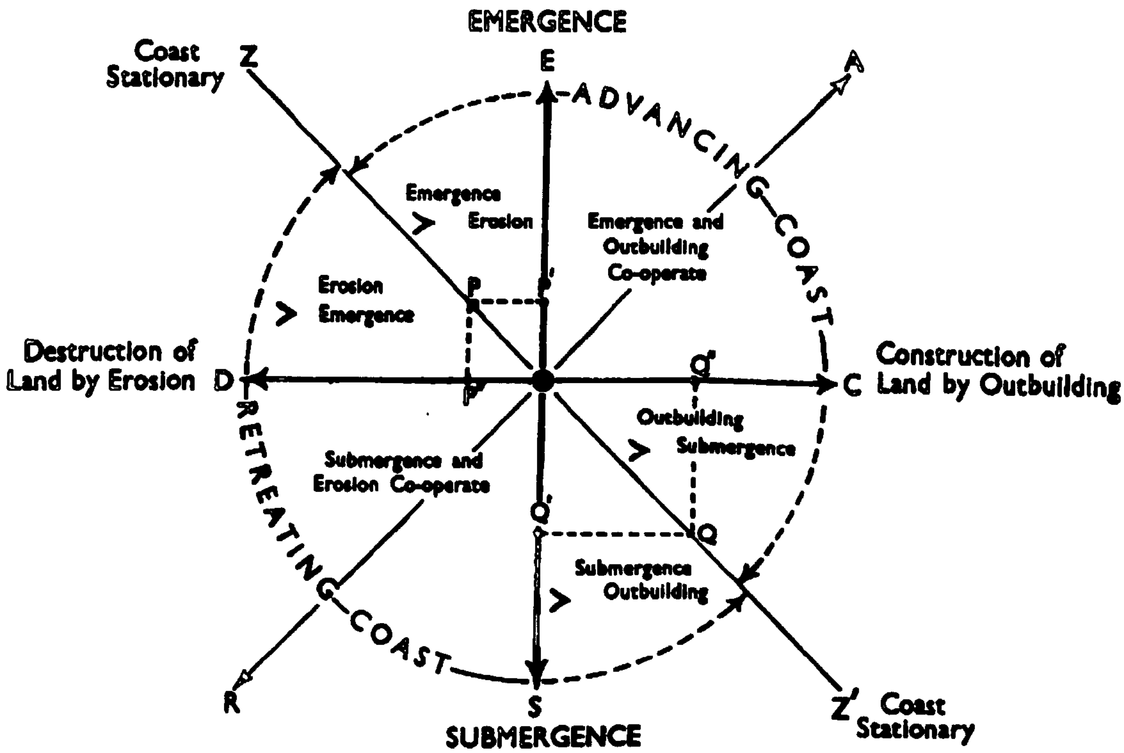


Figure 7.6 Model after Valentin (1952).

Here, the well-known and widely-used diagram - based on an interpretation in Holmes (1972, 1978), and Clowes and Comfort (1998) - is in the form of a circle, with 'emergence' at the uppermost point and 'submergence' at the base defining a vertical axis EOS (referring to the terms in Figure 7.6). The rate of coastal advance or retreat is proportional to the distance from O. The horizontal axis (DOC) represents deposition ('positive' accumulation) to the right and erosion ('negative' accumulation) to the left. The diagonal at right angles (ZOZ^1) represents a 'zero line' along which points like P have equal components of gain by emergence (P^1) and loss by erosion (P^2).

Similarly, points like Q have equal components of loss by submergence (Q^1) and gain by outbuilding or deposition (Q^2). ZOZ^1 represents a state of dynamic equilibrium - a balanced state - where the coastline will remain static on average over the period concerned. This does not mean that erosion and deposition can be neatly grouped with either submergence or emergence - all possibilities may occur - but it is true to say that coastal advance, for example, will be most effective when submergence and erosion co-operate, and coast retreat will be most effective when outbuilding (deposition) and emergence are combined.

Valentin's model is useful in that it can help the flow of logic in any proposed algorithm aimed at software which, in turn, can be used to determine the type of coast for a specific region. This is based on the following cues:

- The Area of Responsibility (AOR) within a particular geographical area
- The physical characteristics of the AOR
- Any user input to influence or override coastal effects

Stochastic methods and fractals, added to process-response modelling, will then furnish details to the coastline being synthesised in the fashion. The Valentin model is therefore a valuable aid to helping determine whether a coastal area is suffering emergence or submergence, whether it is experiencing erosion or deposition, and therefore which sorts of landforms can be expected. The only important variable not modelled here is time. However, mangrove forests are probably extensive enough in the world to be worth inclusion in this work, as are salt marshes/ sand dunes. Reefs - whether coral reefs modern or relic or other fauna/floral deposits are really marine features and are discounted.

This leaves the effluent of rivers into the sea, as well as forms such as tombolos and spits which are caused by tides and currents. These features are quite important and are listed separately:

- **Beaches** are the commonest forms of depositional landforms along any coastline (Small 1989) and may extend as linear features or **tombolos**, where a beach grows as a linear feature away from the main coastline. An example of a tombolo is Chesil Beach, Dorset, UK.

- **Spits** are formed from beach sediments which have been transported by Longshore drift (Small 1989). Since spits accumulate where there is a sharp change in direction of the coastline, then this fact can be used to synthesise spits in the research work. Spits can form into **laterals** (shingle ridges created at right angles to the main feature), and **compound spits**, where lobate forms characterise the feature. An example of a compound form is Blakeney Point, Norfolk, UK.

- **Offshore bars** are related to the above features listed above, in this case the landform runs parallel with the coast and just offshore from it. An example is The Bar, Nairn, Scotland and also Miami Beach, Florida. Larger versions are barrier bars, such as in the region of Martha's Vineyard, NE USA, and the *nehrungen* of the North German - Polish region.

From the above examples it would seem that two conclusions should be drawn; first, the beach-spit-bar formation is too common and large to be discounted in the current work. Secondly, that if such landforms are required for synthesis, then some allowance ought to be made for the action of wind, tide and currents. This latter effect could be built into a process-response model, but initially tides etc. can be represented by other methods, detailed in the section on the algorithm development. For completeness, Small (1989) lists other depositional forms which have already been mentioned and are listed here as follows:

- **Salt Marshes**. These are often associated with creeks, or delta regions

- **Sand dunes**. These are often located at the landward side of beach formations, which is another useful cue for the algorithm development.

7.7 Algorithm Development

The discussion and brief analysis of the various coastal features relevant to this thesis is a prelude to the development of a workable synthesis algorithm. The temptation to include too much detail - for the sake of accuracy and sophistication - is always prevalent, but this should be resisted on the grounds of resources and time. Moreover, a high degree of variation and detail is probably not as important as a general flexibility, functionality and, above all, authenticity.

This section therefore lists the steps and processes which are suggested in order to allow the creation and manipulation of high-fidelity coastal features within the Digital Terrain Models (DTMs) of interest to this research work.

7.8 Assumptions

The following list of assumptions is based on the preceding discussion of coastlines, according to the various models reviewed and the anticipated level of scale and detail in the thesis. The basic terminology and processes involved with the zonation of the coast and wave action was a subject also examined and researched (see Figure 7.7) in order to familiarise MOD users during presentations and Geoforma training.

a1 Coastline is defined as a tract of land-sea interface with a width of up to 1 km and a length extending many hundreds of km.

a2 Coastal landforms are individual features, or sets of features, that characterise a section of coastline. They can be a subset of the coastline, or can compose it entirely.

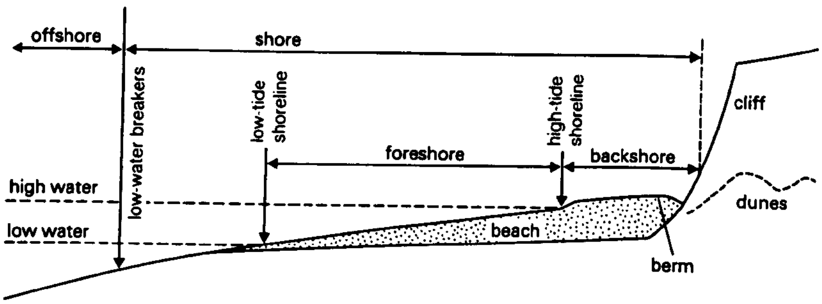
a3 The Valentin model of submergence-emergence, as modified by Holmes and others, is adopted (and a look at modern textbooks confirm that this approach is still taught today - often without reference to Valentin - see for example Clowes and Comfort (1998)). It is acknowledged that the model may be more appropriate to schools than serious geomorphological research but the decision was not made on purely geomorphological grounds.

a4 For each geographical region, an AOR is delimited, within which a stretch of coastline will be delimited. For each area, a look-up table will determine whether submergence or emergence will be the dominant coastline attribute.

a5 The labels *submergence* or *emergence* will influence the types of coastal landforms to be found in the AOR at the land-sea interface.

a6 The physical characteristics of the AOR (height, relief variables, slope, lithology and other attributes), as determined by the analysis phase prior to landscape synthesis, will 'enable' or 'disable' certain landform assemblages prior to coastline synthesis. For example, an upland region of hard, crystalline rocks with the label 'submergence' will most likely result in cliff-bound drowned valleys and headlands.

The zonation of the coast



Basic terms used in the description of waves

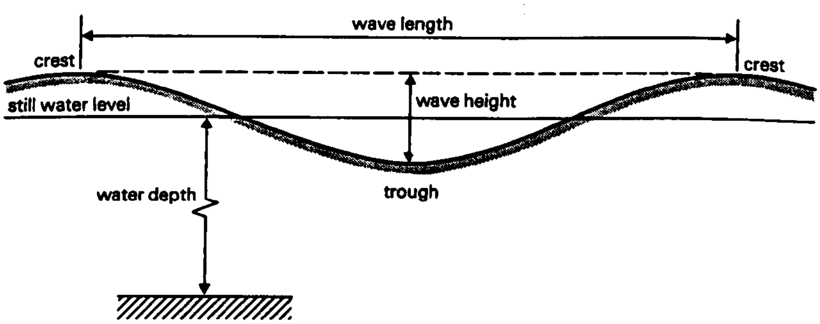


Figure 7.7 (Top) the zonation of the coast and (bottom) basic terms used in the description of waves (after Clowes and Confort 1998)

a7 Synthesis will then proceed, driven by the landscape attributes, scale etc., and with an element of randomness to determine size and shape.

a8 The user will may be given various choices, by means of radio buttons, scroll bars and the like, in a dialogue box, in order to delimit or change some of the landform characteristics of size, orientation or position.

a9 Process-response algorithms may then be invoked to add a further dimension of authenticity to the developing coastline.

a10 As a quality check, a look-up table will have a series of relationships that can be used to check the form, size and position of the landforms. For example, a 'wall; of cliffs in an otherwise low-lying or marshy area would suggest that the modelling process had gone wrong, as this is an 'invalid' relationship. This is difficult to apply to spatial data, but it may provide a 'goodness of fit' measure. Typical checks would be:

- Bars, spits and beaches must have essential proportions, so that their length is many times their width. They must be formed in the direction of the presumed Longshore drift direction (parallel to the trend of the coast).

- Headlands and capes must be composed of relatively hard rocks, not relatively soft material.

- Extensive beach deposits are not found at the foot of steep cliffs

- Cliffs tend to be where high ground meets the sea (and are not found as 'walls' or other unlikely features).

- Spits are formed at points on the coast where there are abrupt changes in the direction of the coastal trend

- Rivers almost never 'fall' into the sea from high waterfalls but grade down to sea level by means of their valleys. The valley types can range from flat delta features with many streams through to estuary forms and rias.

The general sequence of events for the algorithm described above is based on a careful study of Valentin's model plus recent work on coastal geomorphology. In the algorithm, the important decision for the user is to determine where the coastline actually runs. There are no clues in the original reference landscape (on which the classification is based) to help, as the sea can 'face' the land from any direction and in any circumstances of geological phenomenon. Indeed geology poses one of the main problems for the algorithm builder. As mentioned in chapter 2, Jorgensen's (1974) rather unrealistic if robust terrain synthesis program simply floods a range of hills to produce a coast (or an archipelago). This might be ideal for simulating regions such as the Isles of Scilly (which is a kind of 'flooded Dartmoor' as remarked by a fellow passenger during a voyage to the islands in 1990, on sighting the islands for the first time), but it does not have much realism - indeed it is almost deliberately 'non-realistic' in its approach and layout.

Valentin's model does not cover coastline emplacement - as it assumes (quite reasonably) that the worker is well aware where the coastline is positioned. Valentin's model is also difficult to generalise in this respect. As far as 'dial up' terrain - using physiographic templates - is concerned, problems may also be encountered. For example, if the coast of Croatia is being modelled, the Dalmatia-Croatia coastline is noted for running in parallel to the structural trend of the land - in other words it coincides with the grain of anticline-synclinal axes and strata. Thus in this case the user must determine the grain of the land from the parametric analysis phase and deliberately place the coastline in whatever orientation that happens to be. This is no real problem in practice, but the implications must be considered beforehand. Similarly, the Atlantic coast of Ireland has a geological 'grain' at right angles to the coast, hence the many deep indentations. Here too, the user must decide on the coastline orientation, as it cannot be built into the model since the algorithm cannot 'know' whether 'Dalmatia' or 'Atlantic' scenery is required by the user. The great advantage here is that either can be 'made to order'; the great disadvantage is that one cannot generalise or ignore the effects of geology if one is to model the coastal landscapes of the world with true synthesised 'integrity'.

7.9 Results

Relatively few coastline models were constructed, mainly because the intense academic interest in the subject was not shared by the military sponsors, who after all, were concerned with 'results'. This was in spite of the placing of a deliberate TOR on the author. However, some attempts were made to synthesis coastline. The simplest attempts were aimed at synthesised clifflines and beaches, or simply placing sea around the AOR relief and 'flooding' it, while ensuring that geomorphological viability is maintained. Interestingly this is a function of the Terrain Maker synthesised terrain software (Jorgensen 1994).

Another technique involved simply placing a grid of zero height (0 m OD) around a delimited rectangular area surrounding a selected area of terrain. This method was described in Griffin and Gilmour (1980) and was intended to represent the sea around the Land's End peninsula. Although this is not strictly synthesised terrain it uses an existing real-world DEM to synthesise clifflines, and - incidentally - revealed a side-effect of the interpolation that could be avoided by the Geoforma coastline module.

This side-effect is described as follows: it presented an initial problem to Griffin and Gilmour (1980) in that the 2^{nd}-order polynomial interpolation routines gave curved and 'gouged out' cliffs and dipped below 0 m OD (sea level) in order to follow the quadratic curve (see Fig. 7.8 a and b). This was 'cured' by testing for a combined DEM attribute of 'zero metres + coastline', then cutting off or modifying the interpolation routine to produce a sharp break of slope followed by a flat 'sea' (Fig. 7.8b), which was found to approximate the real land surface quite accurately. Similar program logic was put into a test module accessible by Geoforma so that this unwanted effect would be eliminated. The results were that 'realistic' cliffs were created after several attempts.

A synthesised beach and cliff assemblage was also produced (Figure 7.9) by means of synthesising parts of the coastline of the 'imaginary' North Africa. In this case, an AOR was taken and a coastline denoted along a ridge line, using part of the synthesised terrain as cliffs and part as beach (depositional modelling). This was a subset of the author's own software and it did not use SCISSORS (which tended to be aimed at areas not available to the author).

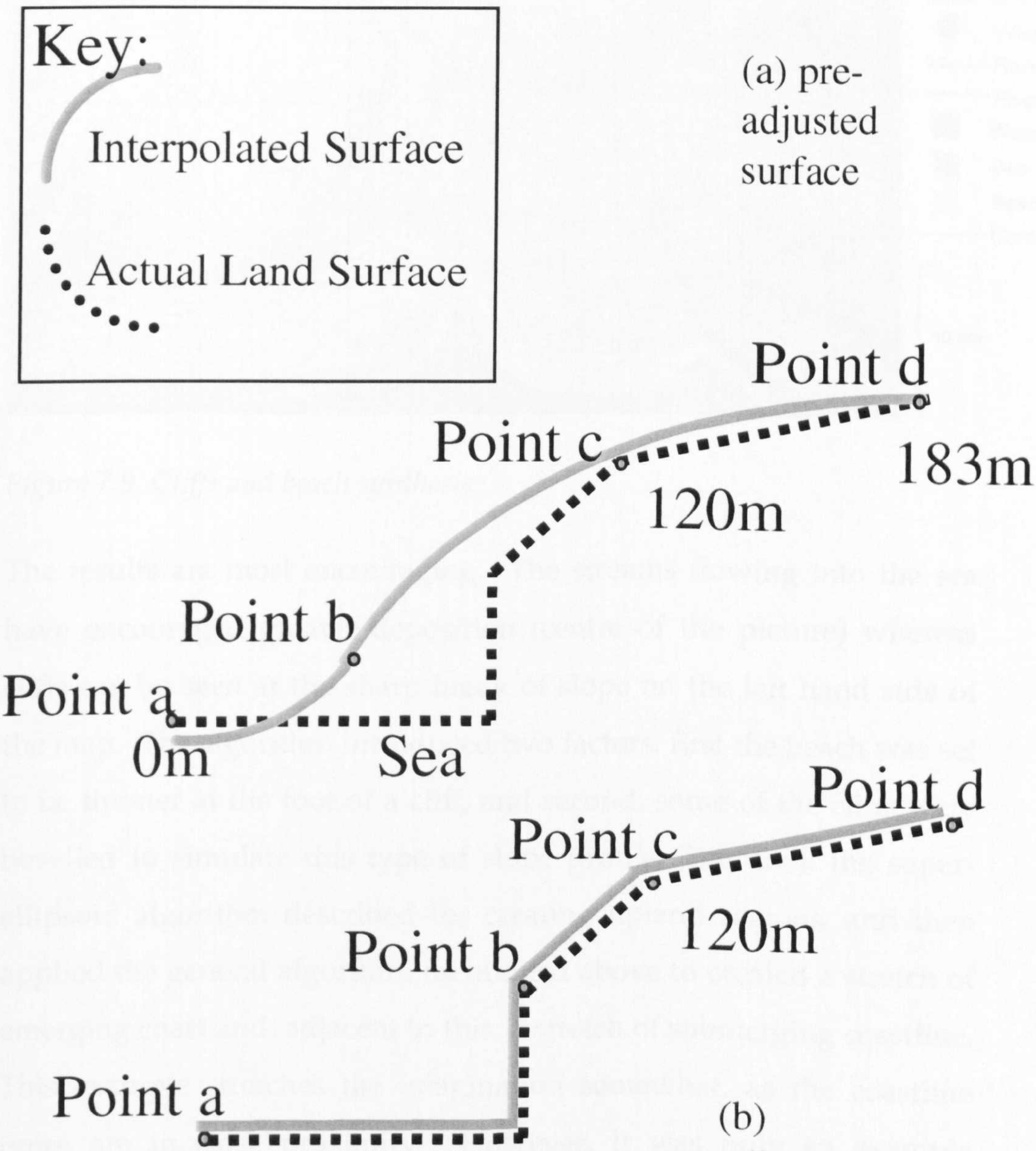


Fig. 7.8 Interpolated and real cliff surfaces

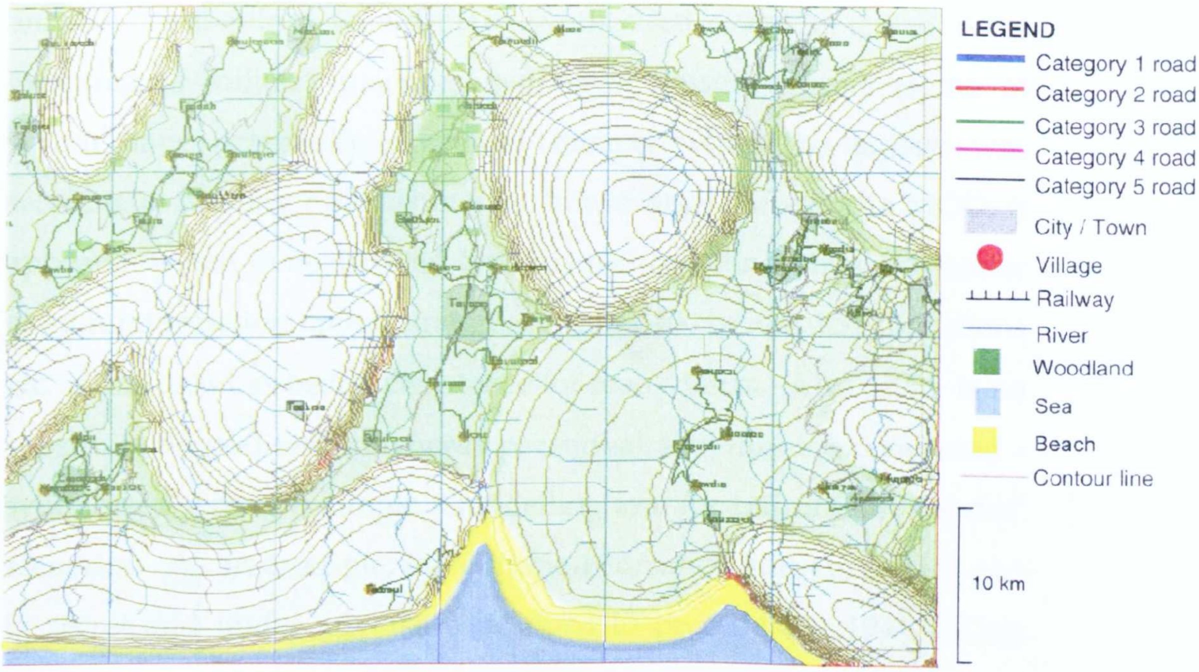


Figure 7.9 Cliffs and beach synthesis

The results are most encouraging. The streams flowing into the sea have encouraged greater deposition (centre of the picture) whereas cliffs can be seen at the sharp break of slope on the left hand side of the map. The algorithm introduced two factors: first the beach was set to be thinner at the foot of a cliff, and second, some of the cliffs were bevelled to simulate this type of slope profile. This took the super-ellipsoid algorithm described for creating upland regions, and then applied the general algorithm mentioned above to created a stretch of emerging coast and, adjacent to this, a stretch of submerging coastline. This example stretches the imagination somewhat, as the coastline types are in close proximity. However, it was only an example intended to test the algorithm. How much of this is fortuitous is open to question as the coast is based on an existing synthesised terrain area, but the author is delighted with the results. The key (legend) was also updated.

Such examples are of great interest to military planners as well as to earth scientists. Interestingly, the planning or training for future amphibious landings would make synthesised coastline terrain most tempting to military planners and naval liaison officers (some of whom have personally expressed interest while the author was working in military establishments), but most of the work in MOD, it appears, tended to be directed towards real coastline, since it is easier to gain information on tidal range, currents, likely weather conditions etc. if this data has been in existence for many years. Also, there is no substitute for real terrain where operational activities are concerned - synthesised terrain is simple a modelling tool for training or 'what if' scenarios. As an example, the enormous detailed survey, carried out in secret and under adverse conditions to precede the 1944 D-Day landings - see Webbe (in Taylor 1978) is testimony to this (an excellent 1:25,300 map of the Normandy D-Day beaches is shown on page 122 - 123 in Goodenough (1982)).

7.10 Conclusion

Although the lack of time and resources meant that synthesised coastline became the 'poor relation' of subjects undertaken in this study, some representative samples were produced in order to exercise the synthesised terrain modelling technology developed by the author, and this has been based mostly on an understanding of the processes at work and the coastal landforms encountered and described in the literature. Coastline modelling has therefore been addressed in this study, but although a certain amount of theoretical and algorithm work was completed (followed by software modification) the prevailing circumstance at the time did not permit an extensive exercise of Geoforma for use with coastal synthesis. This is regrettable, but on a positive note the work did at least achieve the following:

- The study, as reported in this chapter, has addressed the problem of synthesising geomorphologically-viable coastline, instead of merely 'flooding' a fractalised simulated landscape as is done by Jorgensen (1994).

- An insight into some of the key issues, the nature of simulating coastal landforms and relevant literature was gained, and this provides a good basis for future work.

- The combination of adding Valentin's (1952) somewhat underrated model into the existing methods produced an algorithm which - although not intended to be intellectually advanced or highly rigorous - still had enough credibility to allow code changes to be made to Geoforma, with some resultant DEM modifications and images.

- Some synthesised coastal terrain results were achieved and printed but classification restrictions meant that only the example in Figure 7.9 can be demonstrated.

- The original aim to synthesise composite (compound) or multi-phase coastlines was dropped as it was considered to be too difficult to model in the time available, but it can be considered as a possible future aim.

- It is accepted that coastal processes and landforms are geomorphologically complex and sophisticated, thus equally sophisticated models would be needed to do them justice in a truly integrated synthesised terrain simulation suite. This was never the intention of this part of the study; although perhaps a useful glimpse into the *genre* has been achieved.

From a practical point of view, UK forces have a reputation in modern times for taking part in major amphibious landings or evacuations These vary from successful operations such as *Operation Dynamo* - Dunkirk 1940, *Operation Torch* - North Africa 1942, *Operation Overlord* - D-Day Normandy 1944, the Suez landings in 1955 (which were militarily brilliant but politically inept) and the Falklands campaign of 1982. There were also unsuccessful operations (Gallipolli 1915, the Dieppe raid, 1943). Allied planners at the time of World War II surely placed coastal terrain at the top of the list for map acquisition, pre-invasion surveys and training. Should similar situations arise again, a modern planning team would be able to turn to synthesised terrain models for simulation and military training, especially if they were not sure exactly where the blow would fall or if the potential landing area was not initially well supported by maps. All services would potentially be interested, as amphibious landings tend to be combined service operations (i.e. involving the Navy, Army, Air Force and Marines, possibly as well as 'special forces'). Indeed, some discussion was given to coastal simulation at MOD, although the topic was assigned a relatively low priority (hence the lack of detailed results).

CHAPTER 8: INTEGRATION OF PHYSICAL AND HUMAN GEOGRAPHY: THE GENERATION OF SETTLEMENTS, ROADS AND RAILWAYS

Chapter 8

Integration of Physical and Human Geography: The Generation of settlements, roads and railways

8.0 INTRODUCTION

This chapter contains a description of the concepts and thought processes used to link physical synthesised terrain with human 'infrastructure', such as settlements, roads, railways and forests. This process is then used to develop algorithms which in turn are used to produce software. The software modules can then be used to generate settlement patterns and to interconnect these with road networks and railway networks to form an 'infrastructure' which can be overlaid on the synthesised physical landscape. A parametric data set for the generation of culture is also provided.

This chapter deals with two areas of human geography:

- The synthesis of settlements, the links that interconnect them (roads, railways) and the culture parametric set that can be used (for example) to produce synthetic place names.

- The synthesis of 'habitats' - the name given by various sponsors and users to the different vegetation types and land usage.

Finally, the chapter is concerned with some possible future considerations for synthesised infrastructure.

8.2 Settlements

8.2.1 Objectives

The objective of synthesising settlement patterns is to augment the physical landscape in a way so that a pattern of settlements can be established with 'reasonable veracity'. This is clearly difficult to the point of being nearly self-defeating, as a glance at any map will tell an experienced geographer or analyst that the resultant settlement pattern is dependent on a great many variables. Any settlement pattern of - say - two or three centuries in age will have the weight of history, socio-economic and cultural factors behind it - this 'story' can be composed of a mixture of deterministic variables (e.g. avoiding marshy or steep areas), planning or legislative variables, random factors, cultural factors (such as dividing property between offspring), and the wealth of dynamics that control and influence rural, semi-rural and urban settlements.

When it is considered that these factors must be seen in a national, regional and even local context; that wars, historical events and successive waves of immigration may have had incalculable effects, then it is clear that it would be almost impossible to lay down generic principles - even loosely - for settlement patterns. The futility of trying to decide a set of rules a computer can follow is implied by the complexity of some landscapes - see for example Hoskins' (1970) work on the 'Making of the English Landscape'.

This being the case, it was decided to restrict the exercise to well-known areas and draw on the work of respected researchers in the field. In this way it is possible to generate a distribution of settlements of realistic size and population for the region under consideration without incurring any accusations of undue generalisation or 'dabbling'. It should also be stressed that there were commercial constraints at work - the project sponsors needed maps with 'reasonable veracity' and therefore it was felt that there was nothing to lose to attempt to provide them.

This stage of the research also started to see the production of the first 'super-realistic' maps - cartographic representations that are entirely synthesised and yet purport to look like 'the real thing'.

8.2.2 Research and Analysis

Research into possible geographical theories was undertaken. This can be summarised by a brief review at work done on the nature of settlement patterns based on various classifications. One such classification might be: Urban - semi-rural - industrial - rural in developed and underdeveloped countries. Works on terrain evaluation (Mitchell 1991) formed a useful background but tended to concentrate on physical features. However, they were useful for a general guide to land-use. This brief review showed that it would be pointless to introduce the same amount of work into the generation of settlements and infrastructure as has been attempted with the physical landscapes in the previous chapters.

The reasons are cogent: There is simply too much information to be able to formulate simple or helpful rules for potential algorithms. Some of the information is based on opinions or theories, and thus it would be unscientific to attempt to include concepts that are themselves controversial or being refuted by other workers. This thesis clearly addresses the physical side of synthesised terrain; it is this area where the author has credentials, and not in the genre generally known as 'human geography'. Finally, the attempt to introduce settlements is also as an exercise to stimulate further work, rather than any authoritative statement on how infrastructure should be synthesised, although the primary aim, of course, was to produce man-made features which were as realistic and as convincing (yet simple) as possible. Without wishing to appear defensive, this chapter is probably more experimental than the previous three or four, but this had the positive 'side-effect' that it was worth attempting difficult or surprising methods - there was nothing to lose and everything to gain in the search for realistic maps. Also, there is an element of lateral thinking in some parts of this chapter, and unlike the physical synthesised terrain not all the algorithms needed to be carefully based on established work for the sake of geomorphological (or geographical) credibility.

Most of the background research for this chapter included investigating theories by geographers and economists such as Christaller (1933 translated 1966), Weber (1909), Lösch (1954), Johnson (1972) and Dickes and Lloyd (1990). Also examined in detail was the work of Von Thünen (1826, 1850, 1867), who laid down some simple but profound ideas were probably the first serious treatment of spatial economics. This also gave a useful model that could, if desired, be used to 'tune' the settlement algorithm. It should be noted that there are dozens of WWW (web) sites dedicated to this pioneer, and that his work is still relevant today. For Geoforma, of course, it had an advantage in that it was simple.

However, after much consideration the approach first outlined by Christaller in the 1930s was adopted because of its general applicability to some areas, its relative simplicity and popularity with the MOD sponsors, and its flexibility in relation to the Geoforma algorithms. Also, Christaller is well-known, if rather dated, and while it is by no means perfect (since it is not universally applicable) it is simply applied (in the particular circumstances where the research was done). Also it was found to illustrate the tenets of the algorithm admirably. Further academic research into the literature was probably necessary, but regrettably it was curtailed by the sponsor due to the lack of resources and the need to meet deadlines.

The geographical theory that is to be used in the generation of settlements, determines which factors of the real terrain would require analysis with regards to settlements. In the case of Christaller, this included factors such as the size of settlements, the distance between settlements of similar sizes, the height difference in terrain where the settlements are located.

The majority of road and rail links are determined from the location of settlements, however, some roads, particularly smaller roads require additional analysis as to their location, density and length.

8.2.3 Results of Research and Analysis

Christaller's Central Place Theory (CPT) was first developed by Walter Christaller in 1933 and applied to North Germany (which, coincidentally, is also part of one of the study areas in this thesis). The theory was based on the following hypothesis: The larger the city, the larger its tributary area of customers for that city or settlement.

Ideally each settlement serves a circular area around it, but unless these circular areas overlap, gaps or 'unserved' areas will be left. To over come this problem the circles were overlapped equally to form equilateral hexagons. These hexagons form the basis of Christaller's CPT.

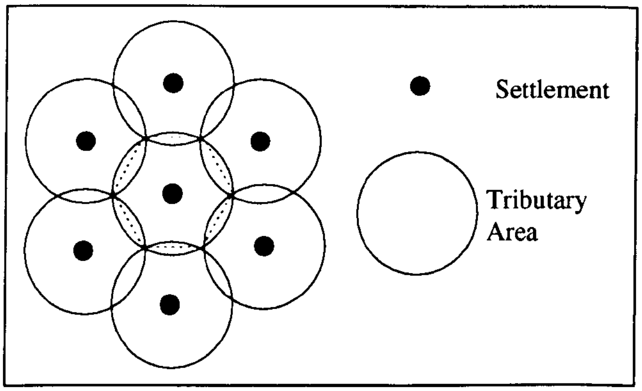
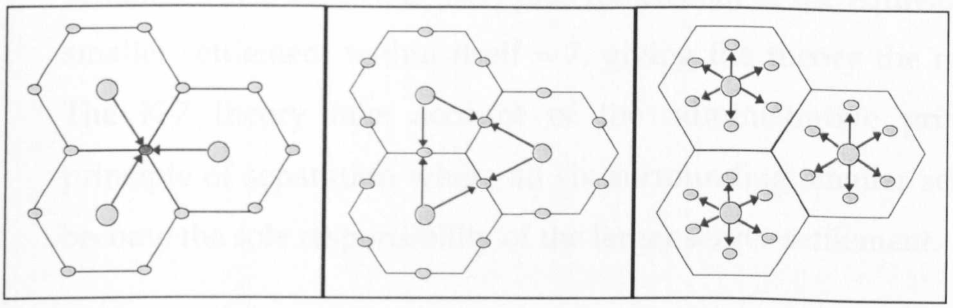


Figure 8.1. Settlement Tributary Areas

Settlements are separated into categories and are considered to be of the same category if they are of a similar size in terms of service population. Also settlements of the same category tend to be equal distances apart. Christaller used **seven** categories in 1933 for Germany. It was found, on inspection of the relevant maps of Central Northern Europe, that Geoforma would need to use up to **nine** categories. This increase is due to population growth since 1933 resulting in settlements that were once deemed too small to be considered, growing to an influential size, i.e. the settlements have become large enough to be of service to surrounding smaller settlements. The server settlement is based at the centre of a hexagon and surrounded by six settlements of one category smaller. Christaller developed three main types of CPT, namely K-3, K-4 and K-7.

The distances between settlements and the location of settlement with relevance to each other is dependent on which K theory is being used.



K-3 K-4 K-7

Figure 8.2. Christaller's Central Place Theory (CPT)

Each smaller settlement is served by three larger settlements. Therefore each larger settlement receives a third of the custom of each of the smaller settlements around it. Thus the total custom a larger settlement will receive is (6x1/3) plus the custom of the equivalent sized smaller settlement within itself = 3, giving the theory its name K-3. The K-3 theory is based on the principal of maximum server opportunity, thus each settlement aims to place itself equi-distance from as many larger server settlements as possible, the maximum being three as shown.

Each smaller settlement is served by two larger settlements. Therefore each larger settlement receives one half of the custom of each of the smaller settlements around it. Thus the total custom a larger settlement will receive is (6x1/2) plus the custom of the equivalent sized smaller settlement within itself = 4, giving the theory its name K-4. The K-4 theory is based on the traffic principle to account for the situation where the cost of transportation is significant. It allows as many important places as possible to lie on the route between two larger towns.

Each smaller settlement is only served by one larger settlement. Therefore each larger settlement receives the entire custom of the smaller settlements around it. Thus the total custom a larger settlement will receive is (6x1) plus the custom of the equivalent sized smaller settlement within itself = 7, giving the theory the name K-7. The K-7 theory take account of the administrative principle or principle of separation where all six surrounding smaller settlements become the sole responsibility of the larger server settlement.

Christaller's theory is based on a perfectly flat land with an equal distribution of all resources. In the real world this is not the case but key elements of the theory, (e.g. the average equi-spacing of settlements of the same size), has been fitted to many parts of the world and seen to be generally true. In an ideal situation all six smaller settlements will be placed around the larger server settlement but due to terrain constraints this is not always possible. Thus as many settlements as possible, up to six, are placed. It was found by trial and error that out of the three countries analysed Germany tended to follow the K = 3 principle, and Poland and Morocco (the final two of the three test areas) followed the K = 4 principle.

8.2.4 Settlement Populations

The population of settlements decrease at each category by a specified factor. Christaller found that for the K-3 theory a settlement's population decreased by a factor of three (note that this is also the K number). In an attempt to extend this theory with population data from other countries it was found that for a country which places settlements according to the K-4 theory (e.g. Poland) a dividing factor of 4 can be used.

8.2.5 Method Used To Generate Settlements

The following steps are used in the generation of settlements.

- Find the largest area to accommodate the first settlement. The size of which is determined from the parameter set and which Category of settlements need to be generated.

- From the centre point of the area found, find the ideal centre locations for all other settlements using Christaller's CPT.

- Try and find a suitable location for each of the ideal settlements that are within the terrain matrix.

8.3 Finding Flat Areas

Within the Culture Parameter set there is a value for the 'Maximum Height Difference'. This value determines the flatness of the land on which a settlement can be placed. For example in the case of the Hartz Mountains, Germany, the Maximum height value is set to 70 metres. This means that when searching for a flat area, the elevation points can only ever be up to 35 metres difference above or below the search area starting elevation point.

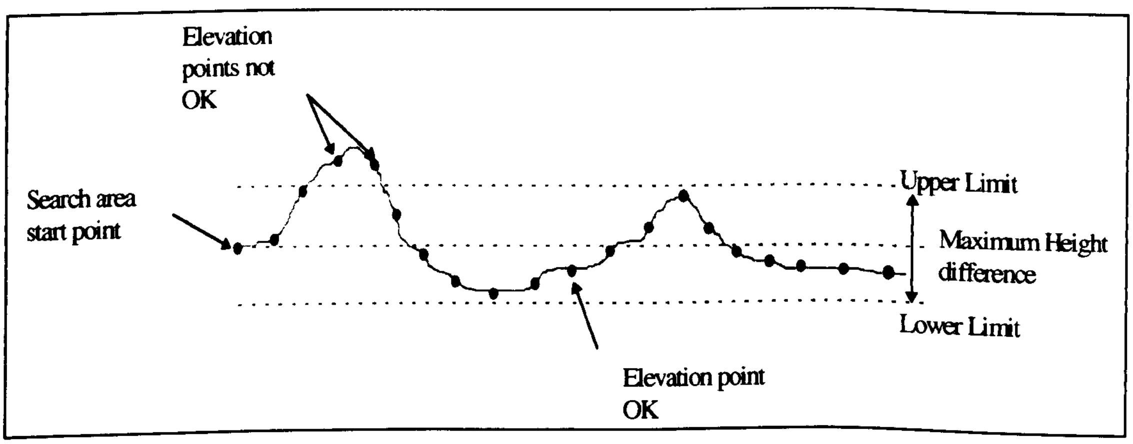


Figure 8.3. Finding 'Flattish' Areas

8.3.1 A Settlement's Areal Size

The areal size of a settlement is the surface area on the ground that the settlement covers, e.g. square kilometres. This information is required so that possible sites can be found within the synthetic terrain for the settlement, e.g. an area of relatively flat land that is also large enough to accommodate the settlement. A transformation formula has been developed so that if the population of a settlement is known, the areal size can be calculated. See Equation (1).

$$\boxed{\ln Size = \left(0.628 \times \ln Population^{3/4}\right) - 1.84} \qquad (1)$$

To find an area within the terrain matrix that can accommodate the settlement, the elevation points have to be checked and they have to be within the area limits of the required size of settlement.

The method used to search for a suitable settlement location is outlined below:

- Set the limits of the search area
- Set the limits for the settlement template
- Position the template over the Terrain matrix within the search area.
- Check the elevation points are within the limits set by the Maximum Height Difference value (*).
- Calculate the actual area of 'flattish' land from the number of elevation points that are within the height constraints and within the settlement radius.
- If the area is within the limits for the areal size of the settlement then a possible settlement location has been found.
- Re-position the settlement template over the next set of elevation points and repeat from (*) until entire search area has been covered.

- The final location chosen for the settlement is the one that has an actual size larger than the lower size limit, but less than the upper size limit, and also has the most elevation points within the entire template size that are within the height constraints (i.e. not just the points within the settlement radius).

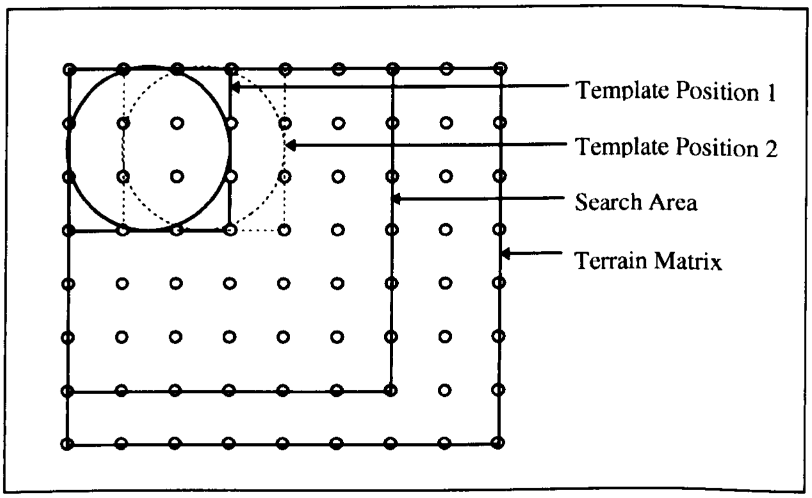


Figure 8.4. Template Search for a Suitable Settlement Location

8.3.2 Settlements As Polygons

A settlement is initially stored as an array of flagged points (i.e. computer indicated by means of set or cleared bits) that make up the entire settlement. However, it is more appropriate to store just the settlement boundary as an array of points that can be displayed as a polygon. To 'Polygonise' the settlement, the boundary edge points have to be identified, and stored in order. To do this the following method is used (using iteration where necessary, for example if a condition 'fails' the process is restarted).

1) Find edge points along the top

- Start at the top left corner.
- For each column move down each point in the columns until the first flagged settlement point is found.

- Add the flagged settlement point to the array of boundary points.
- Remember the position of the last point found.

2) **Find edge points down right hand side**

- Starting one row below the last point
- For each row move left through each point in the row until the first flagged settlement point is found.
- Add the flagged settlement point to the array of boundary points.
- Remember the position of the last point found.

3) **Find edge points along bottom**

- Starting one column to the left of the last point
- For each column move up through each point in the column until the first flagged settlement point is found.
- Add the flagged settlement point to the array of boundary points.
- Remember the position of the last point found.

4) **Find edge points up left hand side.**

- Starting one row above the last point
- For each row move right through each point in the row until the first flagged settlement point is found.

- Add the flagged settlement point to the array of boundary points.
- Stop when the first point is reached.

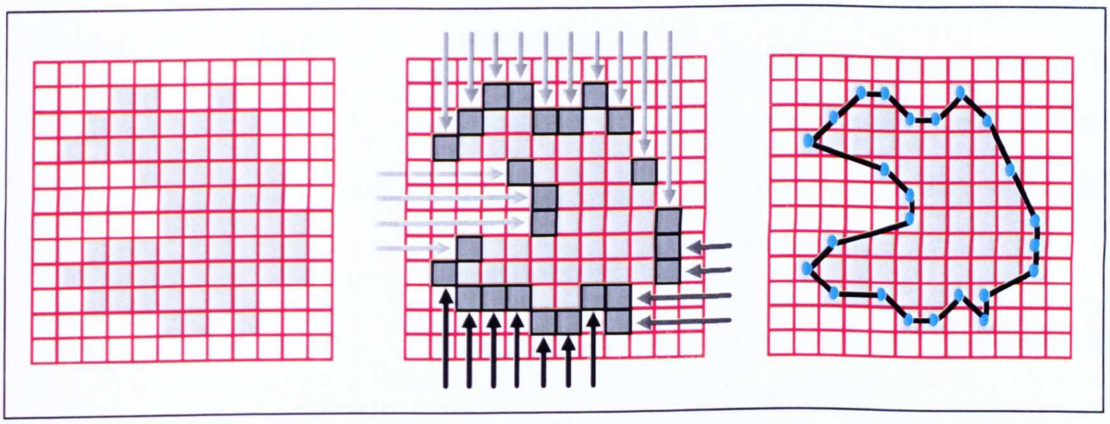


Figure 8.5. Settlements as Polygons

8.4 Settlement Name Generation

Each settlement generated that is within the area of responsibility (AOR) has a name assigned to it. The place name is appropriate to the country that has been synthesised. A table of place name prefixes and a table of place name suffixes for different countries exists in the database. A name is generated by randomly selecting a prefix from all prefixes that are relevant to the country and a suffix from all suffixes that are, again relevant to the country. For example, if the country is Germany then a place name would be generated in the following way (Figure 8.6):

Figure 8.6 Place name generation

Prefix	Suffix	Possible Place Names
Stutt	burg	Stuttburg
Heidel	dorf	Stuttdorf
Eisen	gart	Stuttgart
		Heidelburg
		Heideldorf
		Heidelgart
		Eisenburg
		Eisendorf
		Eisengart

If the third prefix was randomly chosen, then the prefix would be ***Eisen***. If the second suffix in the list was chosen, then the suffix would be ***dorf***.

The resulting place name would be

Eisen + dorf = ***Eisendorf***

8.5 Roads

8.5.1 General Rules

Roads run between the following possible nodes:

- settlement to settlement
- settlement to a point on a road
- road point to road point
- road point to settlement.

There are six categories of roads, Category 1 being the largest road type e.g. Motorways. Category 6 the smallest. In general category 1 Roads run between the larger Settlements and likewise the smaller category roads run between the smaller Settlements. Category 6 roads run generally between road point to road point. The larger the category of road, the less tolerant to gradient the road is. However, the larger roads cut through the land more with cuttings and tunnels, while smaller roads follow the terrain. The larger roads also tend to be straighter while the smaller roads wind round and up hills etc. Larger category roads do not always go to the centre of the large settlements. Instead they go to become a ring road, they also try to avoid (by-pass) smaller settlements that are in between the two settlements. Note that the categories are 'virtual' - what is a motorway in Europe can simply be a good trunk road in a third-world country. Similarly, a Category 6 road in Europe is merely a footpath (or goat-track) in certain other areas. This is easily defined by the user and has no or little bearing on the algorithm.

8.5.2 Method used to create roads

To create or 'run' a road, a *Start Point* and an *End Point* are required. These points must be within a certain distance from each other, and once these have been identified then the direction from the start point to the end point is calculated. The algorithm states that a road will always try to take the most direct route, however terrain constraints will mean that the road may deviate from the direct path. How much it can deviate depends on the terrain, and the type of road being generated, the angle of deviation from the direct route for each category road, and the maximum allowable gradient for each category.

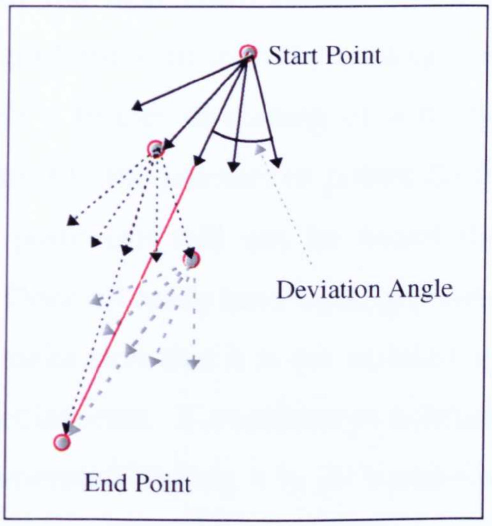


Figure 8.7 Running Roads

As shown in Figure 8.7 the algorithm tests the gradient at a point some arbitrary distance along the direct route. It will then compare this to the gradients at points either side of the initial point, to find the point which gives the minimum gradient. If two points have the same gradient which is lower than the current minimum gradient, then it will randomly chose one of them. It then checks the final minimum gradient with the gradient limit, if the gradient is within the limit then the point that gave this gradient is the next point in the road. If after checking all points within the deviation angle limits, the minimum gradient is outside the gradient limit, then the next point along the direct route is checked.

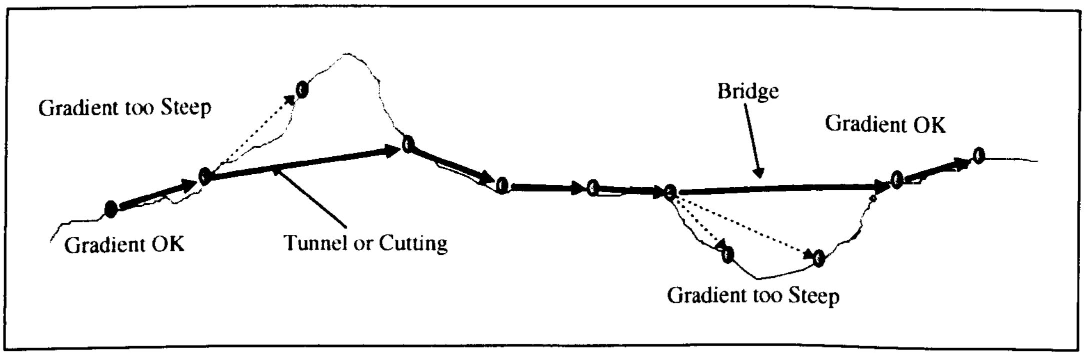


Figure 8.8 Tunnels, Cuttings and Bridges

If the test at the next point results in the minimum gradient being within the gradient limit then the road can continue to this new point, and in effect a tunnel or cutting or a bridge is made (see Fig. 8.8). There is a limit to the number of points (3) that can be skipped in this way. If a point can still not be found then the road will not be generated. Once all roads have been generated then each settlement is checked to make sure that it is not isolated and there is a road linking it to other settlements. If a settlement is found to be isolated then new roads are generated linking it to its nearest neighbouring settlements. As an aside, 'nearest neighbour' analysis is a common technique in the earth sciences (Okabe *et al* 1994) - interestingly the current research puts - as it were - the nearest neighbour analysis 'into reverse', so instead of counting distances between existing settlements, a similar technique can be 'played back' to position the likely settlements based on the statistical technique.

Identified but not emplaced in the algorithm was the author's observation that roads tend to take a drastic 's-shape' bend to go over or under a feature such as a canal, railway or river, but only if the road approaches the obstacle at a very acute angle. The reason is obvious; it avoids the road builders from having to construct long bridges or tunnels. No references could be found to this phenomenon, but it is mentioned for completeness. The author decided that this refinement was not worth the effort to include it in the algorithm.

8.5.3 Avoiding Settlements

Larger Category of roads tend to avoid smaller settlements as they run between the larger settlements. This is done by checking each road section to see if it crosses a Settlement boundary. (See Figure 8.9).

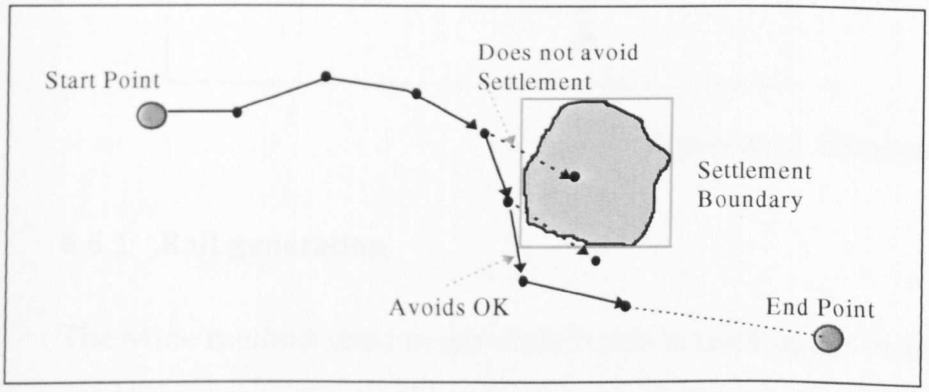


Figure 8.9 Settlement Avoidance

Each road point that is tested for gradient also has to be tested for intersection with settlements for the larger category roads. The nearest settlement to the road point is found. This settlement must not be the same settlement as the start or end settlement. Once the nearest settlement is known, then the road section is tested for intersection with the settlement boundary. If the road sections end point is within the Settlement boundary or the road section crosses the boundary, then the road point is discarded and an alternative route is found.

8.6 Railways

8.6.1 General

Railways run between the larger settlements. Any smaller settlements that are between the two are generally included in the rail route. If rail routes between different settlements follow a similar route to another rail route (i.e. via the same settlements) then the same track is used. See Figure 8.10.

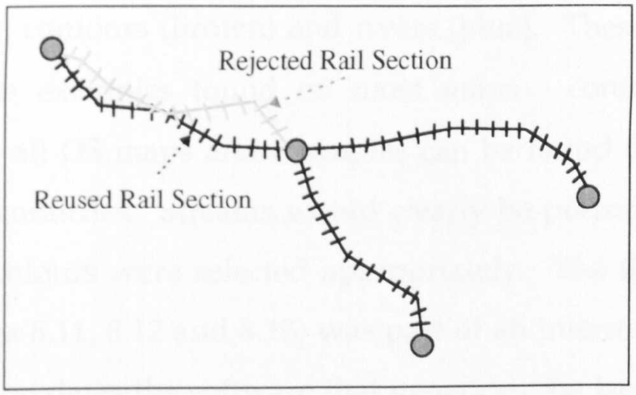


Figure 8.10 Reusable Rail Track

8.6.2 Rail generation

The same method used to generate roads is used again to generate rail roads, however the gradient limit is much lower, set at 1:40. The rail road also tend to be relatively straight, similar to the larger category roads.

8.7 Culture Parameter Set

The following paragraphs discuss the parameter set associated with culture, including roads etc.

8.7.1 Introduction

Using approaches and a philosophy similar to the terrain topology parameter set, culture also has been assigned a parameter set that is stored in the database associated with Geoforma. These parameters allow the user to control the culture that is generated. By carrying out simple analysis new parameter sets can be created for different regions. There are also eight standard/default/system predefined sets of parameters for eight different regions. These can be altered by the user to get different results.

Initially some tests were run with real terrain (based on an elevation matrix or DEM), to position an urban area (the red circle), roads (black), contours (brown) and rivers (blue). These colours follow the obvious examples found on most maps - contours are brown on almost all OS maps and examples can be found from the maps from many countries. Streams would clearly be portrayed in blue and the other colours were selected appropriately. The illustration sequence (Figures 8.11, 8.12 and 8.13) was part of an intermediate test print-out and it predates the software that generates the key or legend - itself a time-consuming procedure. For this reason please note that some of the early results did not include a key: 8.13 shows a test exercise map where blue represents roads, brown lines are contours at 50m intervals, black lines are the rail network and the red disc represents a major town.

8.7.2 List of Culture Parameters

See Table 8.1 for a full list of all the parameters required for culture generation.

FIELD NAME	DESCRIPTION
ID	Record Identifier
Region	Parameter Set Region
K Value	Christaller's Central Place Theory ' K - Value' (3, 4)
Category 1 Population	Population of Largest Settlement
Category 1 Distance	Ideal Distance Between Largest Settlements
Max Height Difference	Maximum Height Distance used for finding large flat areas to accommodate settlements
Max Dist Mean	Mean Maximum Distance for the length of Category 6 roads
Max Dist Std Deviation	Standard Deviation for Maximum Distance for the length of

FIELD NAME	DESCRIPTION
	Category 6 roads
JunctionMean	Mean Distance between junctions of Category 6 roads with other roads
JunctionStdDev	Standard Deviation between junctions of Category 6 roads with other roads
TargetCat6RoadLength	Total length of Categry 6 road to be generated
Cat1RoadGradient	Maximum allowable Gradient for a Category 1 road
Cat2RoadGradient	Maximum allowable Gradient for a Category 2 road
Cat3RoadGradient	Maximum allowable Gradient for a Category 3 road
Cat4RoadGradient	Maximum allowable Gradient for a Category 4 road
Cat5RoadGradient	Maximum allowable Gradient for a Category 5 road
Cat6RoadGradient	Maximum allowable Gradient for a Category 6 road
RailRoadGradient	Maximum allowable Gradient for a Rail road
Cat1RoadGenerate	Boolean indicator for the generation of Category 1 roads
Cat2RoadGenerate	Boolean indicator for the generation of Category 2 roads
Cat3RoadGenerate	Boolean indicator for the generation of Category 3 roads
Cat4RoadGenerate	Boolean indicator for the generation of Category 4 roads
Cat5RoadGenerate	Boolean indicator for the generation of Category 5 roads
Cat6RoadGenerate	Boolean indicator for the generation of Category 6 roads
Cat1SettlementGenerate	Boolean indicator for the generation of Cat. 1 Settlements
Cat2SettlementGenerate	Boolean indicator for the generation of Cat. 2 Settlements
Cat3SettlementGenerate	Boolean indicator for the generation of Cat. 3 Settlements
Cat4SettlementGenerate	Boolean indicator for the generation of Cat. 4 Settlements
Cat5SettlementGenerate	Boolean indicator for the generation of Cat. 5 Settlements
Cat6SettlementGenerate	Boolean indicator for the generation of Cat. 6 Settlements
Cat7SettlementGenerate	Boolean indicator for the generation of Cat. 7 Settlements
Cat8SettlementGenerate	Boolean indicator for the generation of Cat. 8 Settlements
Cat9SettlementGenerate	Boolean indicator for the generation of Cat. 9 Settlements
Cat10SettlementGenerate	Boolean indicator for the generation of Cat. 10 Settlements
RailwaysGenerate	Boolean indicator for the generation of Railroads

Table 8.1. Culture Parameter Set Descriptions

8.7.3 Analysis Required for each Parameter

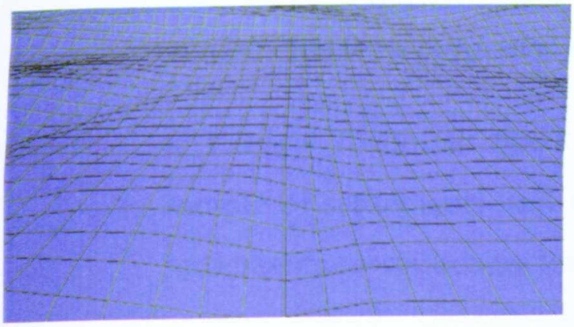


Figure 8.11 Original DTED matrix

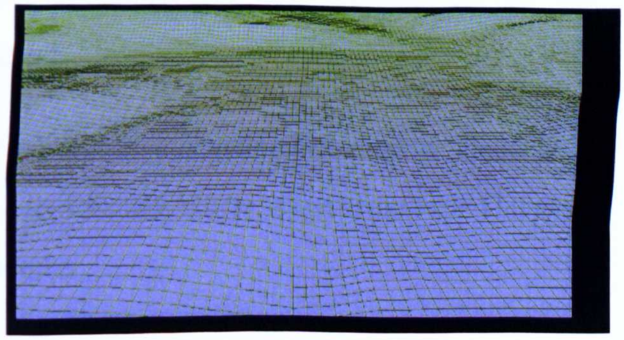


Figure 8.12 Enhanced DTED matrix

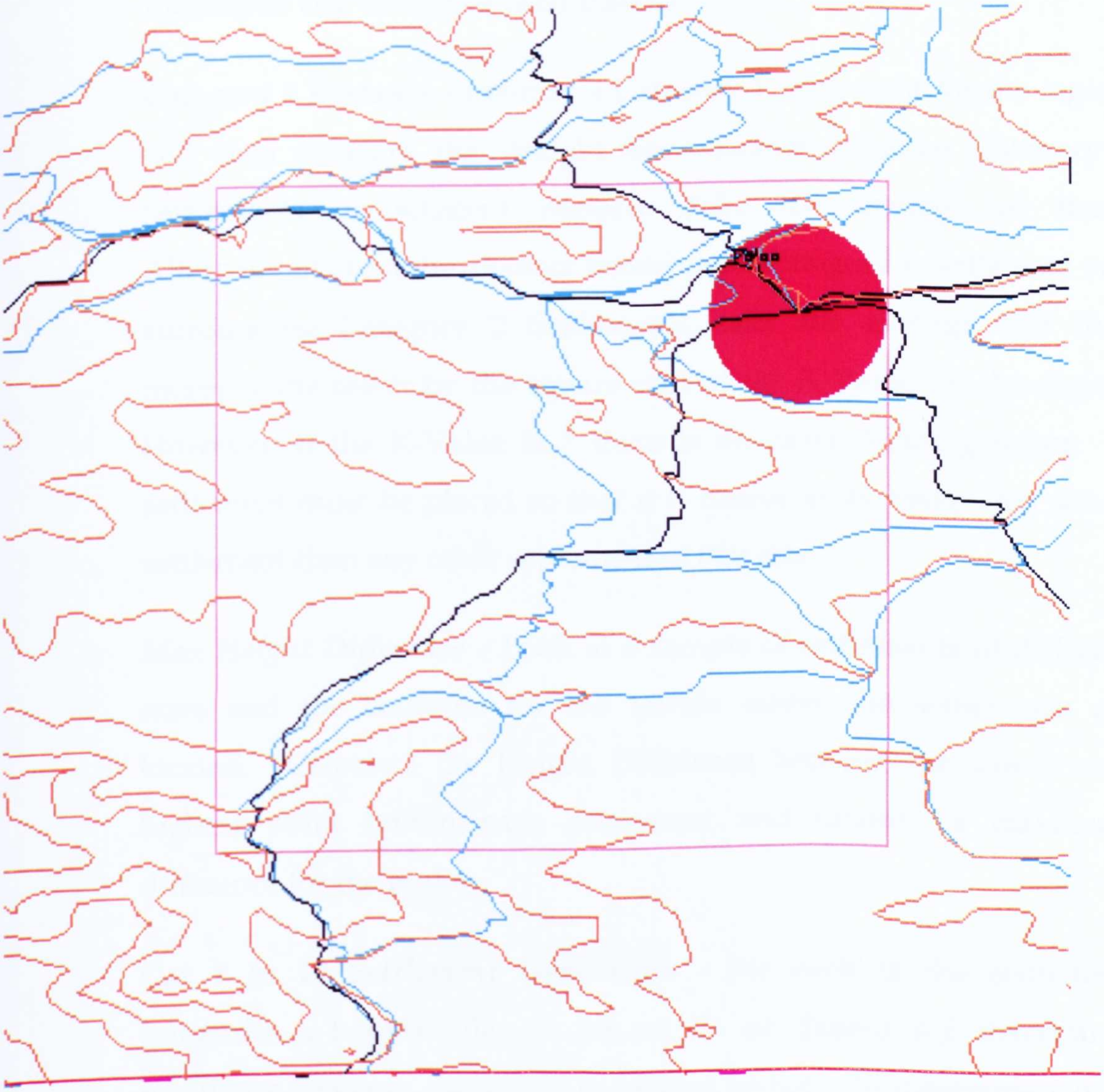


Figure 8.13 Culture synthesised on real world derived elevation matrix

The following parameters are required for the generation of the settlements for a particular region.

K Value - To obtain the K Value for a particular region look at a sample of settlements and try to identify how many service (larger) settlements surrounds each sample.

Category 1 Population - This is usually the population of the capital city for the country to be generated. However, in some cases they may be cities with populations larger than the capitals. The population for the largest city should be used instead.

Category 1 Distance - Identify a Category 1 settlement for the region, and then measure the straight line distance to other Category 1 Settlements of adjacent regions. Take the average of them. Alternatively, find the distance between the Category 1 Settlement and surrounding Category 2 Settlements, take the average and then multiply the result by the square root of the K-Value for the region. However, if the K-Value is 7 there is no exact dividing factor. A settlement must be placed so that it is nearer to its designated server settlement than any other settlement of that size.

Max Height Difference - Look at a sample of settlements of differing sizes and the contours for the terrain where the settlements are located. Calculate the Height Difference between the lowest and highest point within each settlement and identify a maximum difference for the region.

Cat 1 to 10 Settlement Generation - For each of the settlement categories a boolean flag (a bit set (1) or cleared (0)) determines whether a category should be generated or not. To determine which categories should be generated requires the analysis of maps to find out what size settlements are located in the relevant region.

8.7.4 Parameters required for the generation of roads.

Max Dist Mean **(Category 6 roads only).** Look at a sample of the smaller roads (usually little white roads) for the region and measure the straight line length of them. Then calculate the Mean Average of these distances.

Max Dist Std Deviation **(Category 6 roads only).** For the same sample of smaller roads calculate the Standard Deviation for the straight line distance.

Junction Mean **(Category 6 roads only).** Look at a sample of roads that run across the region, and identify the minor road junctions along their length. Calculate the distance between each junction, then using these distances, calculate the Mean Average distance between junctions.

Junction Std Dev **(Category 6 roads only).** From the same sample of roads calculate the Standard Deviation for the distance between junctions.

Target Cat 6 Road Length **(Category 6 roads only).** Calculate the ideal total length of the small minor roads/tracks for the entire area of responsibility (AOR).

Cat 1 to Cat 6 Road Gradients - To obtain the maximum gradient for each road type, analyse maps of the specific region looking at each category of road and the maximum gradient of the terrain that each road runs up or down.

Cat 1 to Cat 6 Road Generation - As for settlements, which category of roads also varies from region to region. A boolean flag is required, to indicate which roads need to be generated.

8.7.5 Parameters required for the Generation of Railways

Rail Road Gradient - As for roads, the maximum gradient for railways also need to be calculated.

Railways Generate - As for settlements and roads.

See Table 8.2. For the eight default Parameter sets.

Table 8.2 Default Parameter Sets

FIELD NAME	RECORDS							
ID	1	2	3	4	5	6	7	8
Region	Low Plateau	North Sea	North Western	Hartz Mountains	Central Lowland	Lublin Plateau	Little Poland	Er Rif Mountains
K Value	3	3	3	3	4	4	4	4
Category 1 Population	3301000	3301000	3301000	3301000	1644500	1644500	1644500	3210000
Category 1 Distance	414000	414000	414000	414000	538200	538200	538200	504000
Max Height Difference	60	40	50	70	30	40	50	40
Max Dist Mean	3262.921	3262.921	3262.921	3262.921	2671.569	2671.569	2671.569	0
Max Dist Std Deviation	1861.169	1861.169	1861.169	1861.169	20282	20282	20282	0
JunctionMean	1506.767	1506.767	1506.767	1506.767	1102.941	1102.941	1102.941	0
JunctionStdDev	1338.656	1338.656	1338.656	1338.656	839.4886	839.4886	839.4886	0
Target Cat6 Road Length	1500000	1500000	1500000	1500000	1400000	1400000	1400000	0
Cat1RoadGradient	25	25	25	25	25	25	25	25
Cat2RoadGradient	25	25	25	25	25	25	25	25
Cat3RoadGradient	25	25	25	25	25	25	25	25
Cat4RoadGradient	35	35	35	35	35	35	35	35
Cat5RoadGradient	40	40	40	40	40	40	40	40
Cat6RoadGradient	40	40	40	40	40	40	40	40
RailRoadGradient	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Cat1RoadGenerate	✓	✓	✓	✓	✓	✓	✓	✓

FIELD NAME	RECORDS							
Cat2RoadGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat3RoadGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat4RoadGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat5RoadGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat6RoadGenerate	✓	✓	✓	✓	✓	✓	✓	✗
Cat1SettlementGenerate	✗	✗	✗	✗	✓	✗	✗	✗
Cat2SettlementGenerate	✗	✗	✗	✗	✓	✗	✗	✗
Cat3SettlementGenerate	✗	✗	✓	✗	✓	✗	✗	✗
Cat4SettlementGenerate	✗	✓	✓	✗	✓	✗	✓	✗
Cat5SettlementGenerate	✓	✓	✓	✗	✓	✓	✓	✓
Cat6SettlementGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat7SettlementGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat8SettlementGenerate	✓	✓	✓	✓	✓	✓	✓	✓
Cat9SettlementGenerate	✓	✓	✓	✓	✗	✗	✗	✗
Cat10SettlementGenerate	✓	✓	✓	✓	✗	✗	✗	✗
RailwaysGenerate	✓	✓	✓	✓	✓	✓	✓	✗

✓ = Boolean Yes

✗ = Boolean No

8.8 Future Considerations

Some future considerations are listed below. Some of these were incorporated into the software, but not all functions were used or tested. For this reason the list is a provisional list of suggestions, all of which have been tested in theory but not necessarily implemented.

8.8.1 Population Density

A possible improvement to the calculation of the Areal Size with respect to Population, would be to include a Population Density Value. This would allow for such cases where the population is concentrated into smaller areas or where the population is spread out over a larger area.

8.8.2 Maximum Settlement Height

A Maximum Settlement Height would mean that a value can be set to stop settlements from being generated above a certain height. It may also be necessary to have a Maximum Height value for each Settlement category. This could then stop larger settlements being built on high ground but would allow smaller settlements, even if there is an area that could accommodate the larger settlement.

8.8.3 Minimum Settlement Height

A Minimum Settlement Height would mean that settlements would not be generated below a certain height. Again, it may be necessary to set different minimum heights for different settlement categories, so there would be a Minimum Settlement Height value for each category.

8.8.4 Generating Roads Within A Set Cost

Research was carried out into generating Roads within a cost. There were two possible methods that were looked into. They are:

(a) To allow only a certain number of Bridges, Tunnels etc. to be used in the construction of roads.

(b) To allow any number of Bridges, Tunnels etc. to be used so long as the cost of building roads stayed within a budget.

Note that the 'S-bend' algorithm expounded in chapter three is also included in the software at this stage. The cost of building a road was dependent on the category of road, the length of the road, the gradient of each road section and a general construction cost. If a section of the road required a bridge or a tunnel then if Method (a) is used then if there is enough bridges or tunnels then the road can continue. If Method (b) is used then if the budget would allow for the cost of building the bridge or tunnel then the road could continue. In either method if the road could not continue then an alternate route that would be cheaper would need to be found. Both methods were implemented and tested but further research would need to be done if either method is to be used.

The revenue of roads could also be a factor. This revenue would alter according to the size of settlements that the road passes through and links.

8.8.5 Generating Railways Within a Set Cost

The same principle used for roads in 4. could also be used for Railways. Again, research would have to be done to see if it is viable.

8.8.6 Settlement Pruning

The probability that a Settlement is actually generated even if the terrain could accommodate it was briefly examined. The effect of implementing the use of a Settlement Probability resulted in the settlement density being reduced. Without this 'pruning' some regions when generated looked cluttered. However, more research would be required in the future to decide if Settlement pruning is statistically valid.

8.8.7 Road Pruning

The probability that a Settlement actually has a road link to each of its Servicing Settlements was briefly looked into. The effect of implementing the use of a Road Probability resulted in the road density being reduced. However, more research would be required in the future to decide if Road pruning is statistically valid.

8.8.8 User Interaction

An alternative approach to considerations 5 and 6 would be to allow the user to select settlements and/or roads to be removed themselves once culture generation has finished. They could also add new settlements and/or roads in a similar fashion.

8.9 Other Geographical Theories

If more geographical and spatially-referenced resource data was held within Geoforma, then it may be possible to incorporate other theories of settlement location besides Christaller. For example, the algorithms sensitive to the approaches and methods suggested by Lösch (1954), Weber (1909), and Von Thünen (1826, 1850, 1867) could be possible additions, on a 'user select' basis at the GUI level (in other words when the user decides what algorithm, and therefore what software module based on the algorithm, can be selected). A comparison of the different methods was, however, beyond the resources, timescales and (in some cases) the training of the programmers assisting the author with the work.

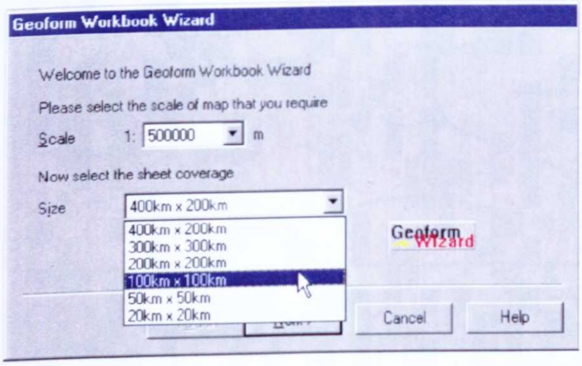
8.9.1 Results

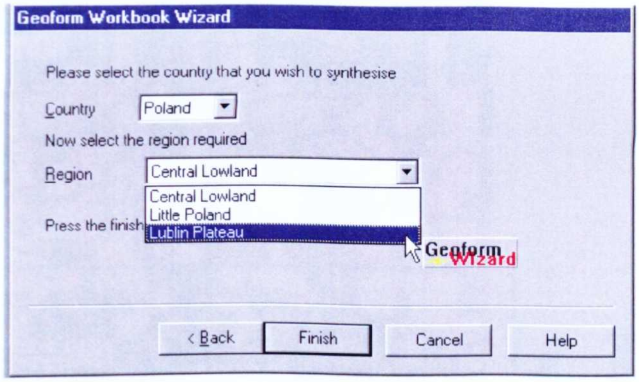
Several interesting results were gained by running Geoforma to produce synthesised terrain maps. Fig. (8.14) shows a raised flatland region of central Europe created by using the Geoforma Wizard. The figure shows a sophisticated synthesised map, with the GUI frames (1 and 2 in the Figure) allowing the user to select scale, extent and then region and sub-region. Names are present (although some adjustment is needed to make them legible), and an interesting - some would say realistic - system of settlements and roads has been created. The only 'give-away' is perhaps the rectilinear nature of the woodland, although the distribution of woodland appears to be satisfactory.

More significant perhaps is Figure (8.15), which shows a Geoforma map of a mountainous region of central Europe (central Europe tended to be a euphemism for 'Germany'). In this map contours are clearly seen, along with woodland (still rectilinear), railways, villages, towns and category 1, 2, 3, 4 and 5 roads. An area of 60km (E - W) by 40 km (N - S) has been generated. This map was used (together with its DTED and DFAD and other digital formats) in actual training simulations, and appears copyright UK MOD, for which the author is grateful. The map shows the sophistication which synthesised terrain can attain, when compared with the estimated costs of $100K (Ref. *MOD minutes; DERA meeting March 9th 1995*) to survey an identical area of 2400 km^2. The author and the sponsors were most gratified and felt that the research had yielded excellent results.

Figure 8.16 shows another usable area, this time with mildly undulating topography and larger urban centres. A 3D perspective view is shown below the image of the 2D map for reference purposes.

1. Select scale and extent





2. Select region and sub-region

3. Resultant cartographic view

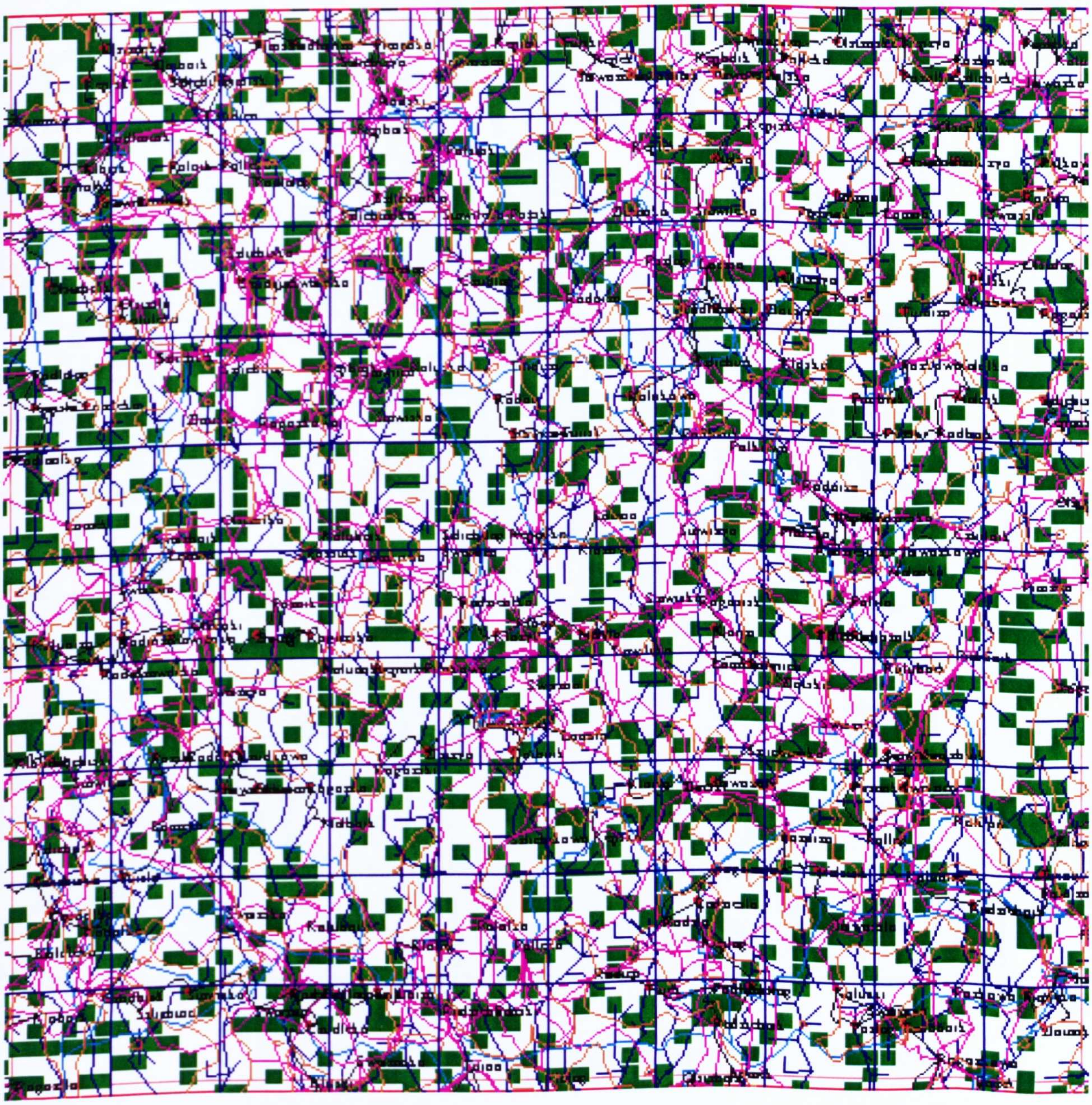


Figure 8.14 Raised flatland region of Central Europe using Geoform wizard

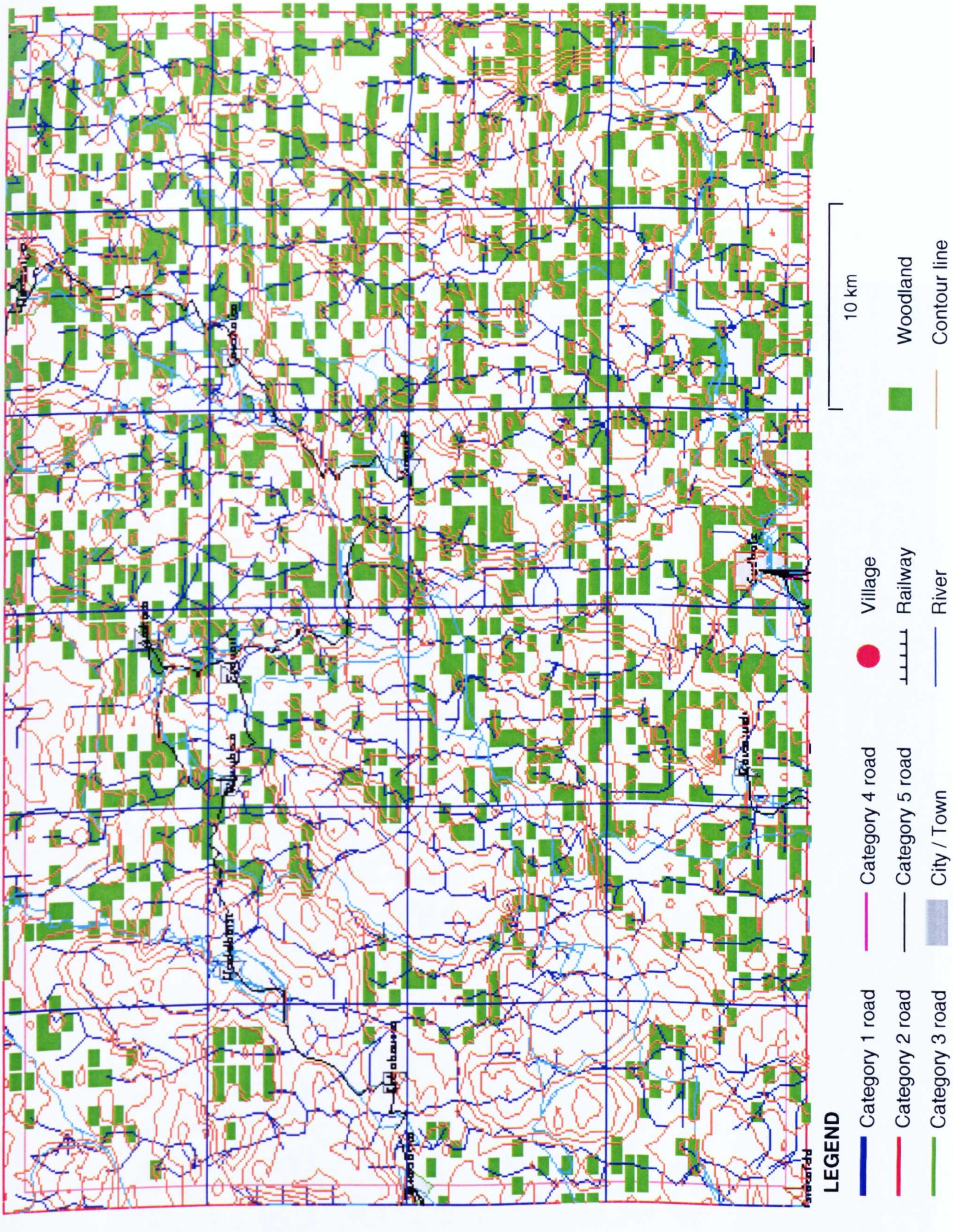


Figure 8.15 Mountainous region of Central Europe

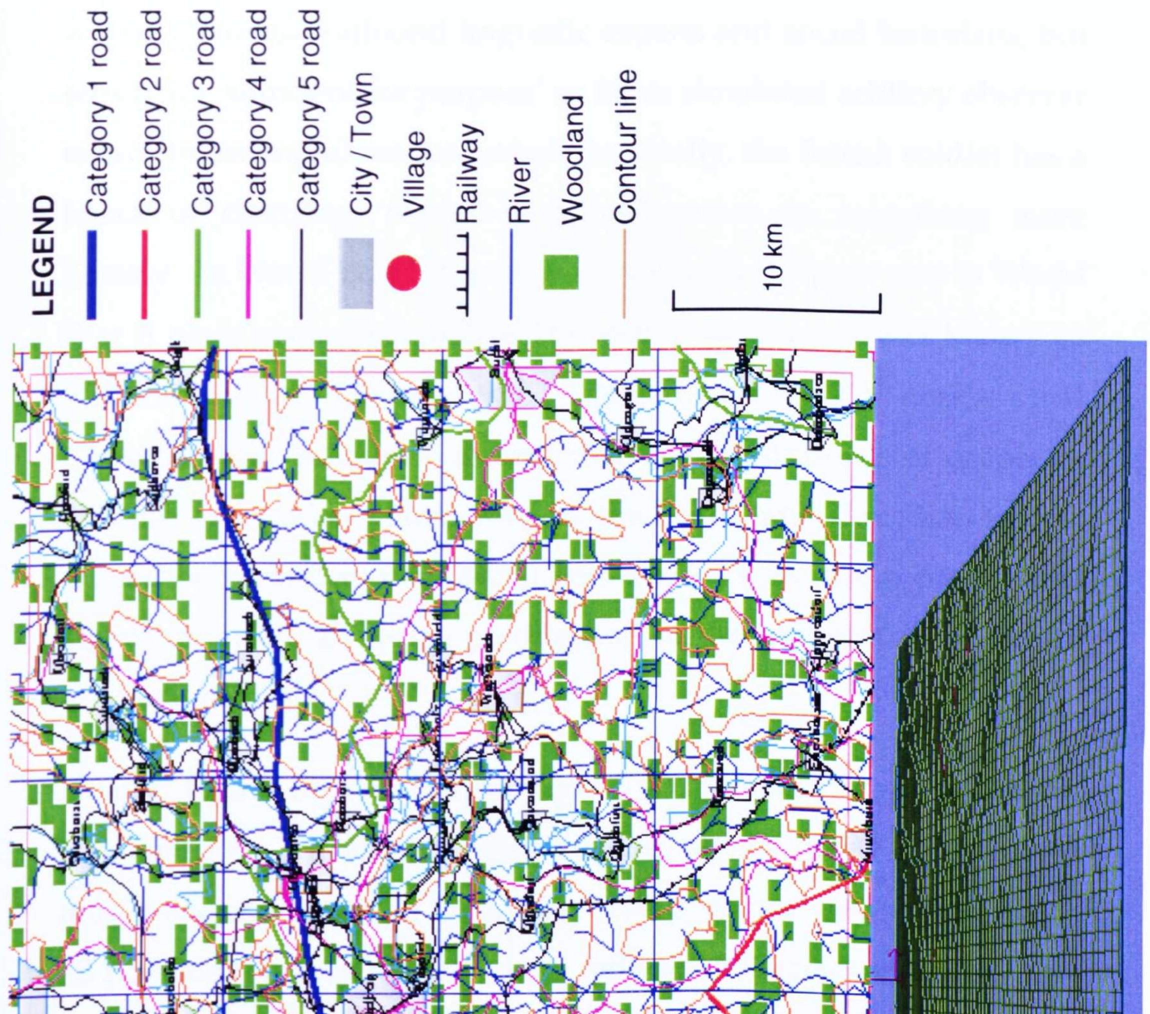


Figure 8.16 Mildly undulating region of Central Europe

The naming algorithm has produced some interesting results which would no doubt confound linguistic experts and social historians, but which are 'sufficient for purpose' as far as simulated artillery observer teams (for example) are concerned. Ironically, the British soldier has a knack of changing 'foreign-sounding' names to something more homely. In World War I 'Ypres' was inevitably 'Wipers' and in World War II place name such as Bois Halbout in Normandy was known as 'Boiled Halibut' (Ryder 1984) while Lewis (1997) notices that Ploegsteerte in Belgium - an area that witnessed scenes of desperate fighting - was called 'Plugstreet' by the British and Canadian troops. Indeed one wonders why MOD bothered to subsidise a place name algorithm at all, given the predilection of the serviceman to corrupt even real names!

Finally, Figure 5.10 in chapter five is an excellent map (somewhat condensed so not all the village names can be seen) of simulated mountainous areas in an 'imaginary' North Africa was created, using all possible category roads, woods, railways, villages and so-on. This map has been shown earlier in the thesis to support upland synthesis, but it is not until this point that the full number of algorithms can be brought to bear (the map is not shown again in order to avoid repetition). It should also be pointed out that the map printing algorithm itself was also a significant piece of work (all the colour maps are intended to be 1:500,000 scale synthesised terrain maps). In Figure 5.10, the relief tends to comprise isolated massifs, but this was a derivation of the baseline physiographic 'source', and can be broadly related to geological formations. Interestingly, this created radial drainage patterns, much to the satisfaction of the author, who predicted this as part of the validation testing. Again a 3D perspective view is included to support the 2D image. Figure 8.17 shows a 'primitive' representation' of the map shown in Figure 5.10 before the

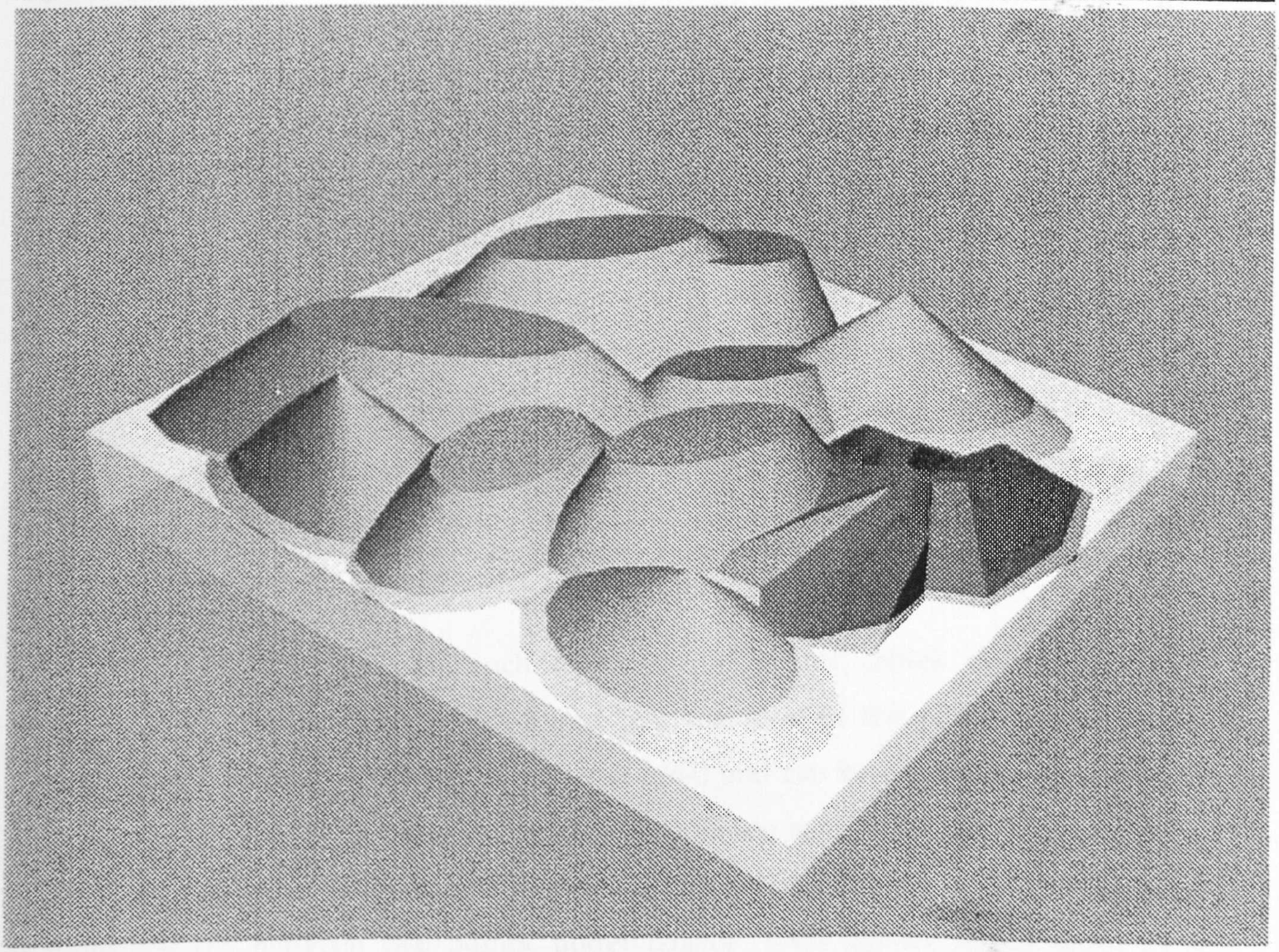


Figure 8.17 Primitive used for region of 'Imaginary' North Africa (in Figure 5.10.

detailed geomorphological process-response and human geography algorithms were added.

8.9.2 Detailed Cultural Features: Power Cables

The DFAD format gives a wealth of 'cultural' features, including objects such as water towers, industrial complexes and so-on. One area that the MOD user asked the team to investigated was the synthesis and modelling of power cables. Also apparently innocuous, pylons stretching power lines across the country side are considered a threat to today's new generation of attack helicopters (such as the Apache) and wire-guided munitions (Anti-Tank Wire Guided missiles or ATWG weapon systems) such as TOW and SWINGFIRE could cease to function effectively if the control wire (normally paid out from a spool inside the missile) came into contact with a high-tension power cable.

To synthesise such features, the power cables themselves were examined. It was found that the form of the power cables follow catenary curves (Geary *et al* 1964) and can be quite easily synthesised in 3D by using quadratic interpolation as a 'short cut'. However, the true mathematical derivation of a catenary curve (a cable suspended between two points, under tension, with gravity acting upon it) is derived from the hyperbolic cosine function, or Cosh.

The expression for a catenary curve is:

$$\mathbf{h = a \cosh x/a}$$

where **a** is the lowest point of the cable from the ground, **x** is the distance from the baseline to the lowest cable point (at **a**), and **h** is the height of the cable at a given distance (**x**). The inter-pylon height must also be taken into account (see diagram) but the catenary curve routine is solved for virtually every likely position (since adjacent pylons tend not to be located with a large elevation differential). The equation assumes that the pylons are of equal height. The cosh function can itself be derived from cosine, although these days most Application Programmer Languages (APIs) and programming language visual tools (such as Visual Basic) support function calls like *cosh* (Figure 8.16a shows the catenary curve for two pylons).

A catenary curve, and is simpler and more accurate than quadratic or cubic interpolation 'fits'. Figure 8.18 shows the geometry of the power cable between two pylons. In the exercises a quadratic fit, a cubic spline fit and a linear fit were used, although in the figure only the quadratic cable 'fit', the actual ground surface and a catenary 'fit' are shown. The quadratic was computationally more efficient but in this case exact results were obtained by using the catenary method, so the polynomial equations were scrapped.

The exercise was done and a simulated synthesised power cable was modelled across a 50 km surface with the pylons 100m apart, even though no production runs were made to incorporate this feature. Although not a frequently-used feature of Geoforma, the algorithm and the software remains available should the sponsors or any other agency wish to revive it.

8.9.3 Other Results: general

Other figures of general interest - as they represent stages in the creation of a synthesised fully functional terrain region - are shown in the sequence of figures, from Figure 8.19, which shows a trend surface before erosion. Figure 8.20 shows a 3D view of a DTED matrix for a 5km X 5km area of Germany, whereas 8.21 shows the contours for the same area at 100m intervals. Returning to Figure 5.10 in chapter five, which shows mountains in an 'imaginary' North Africa with roads, settlements etc., this map was used as one of the main exercises to

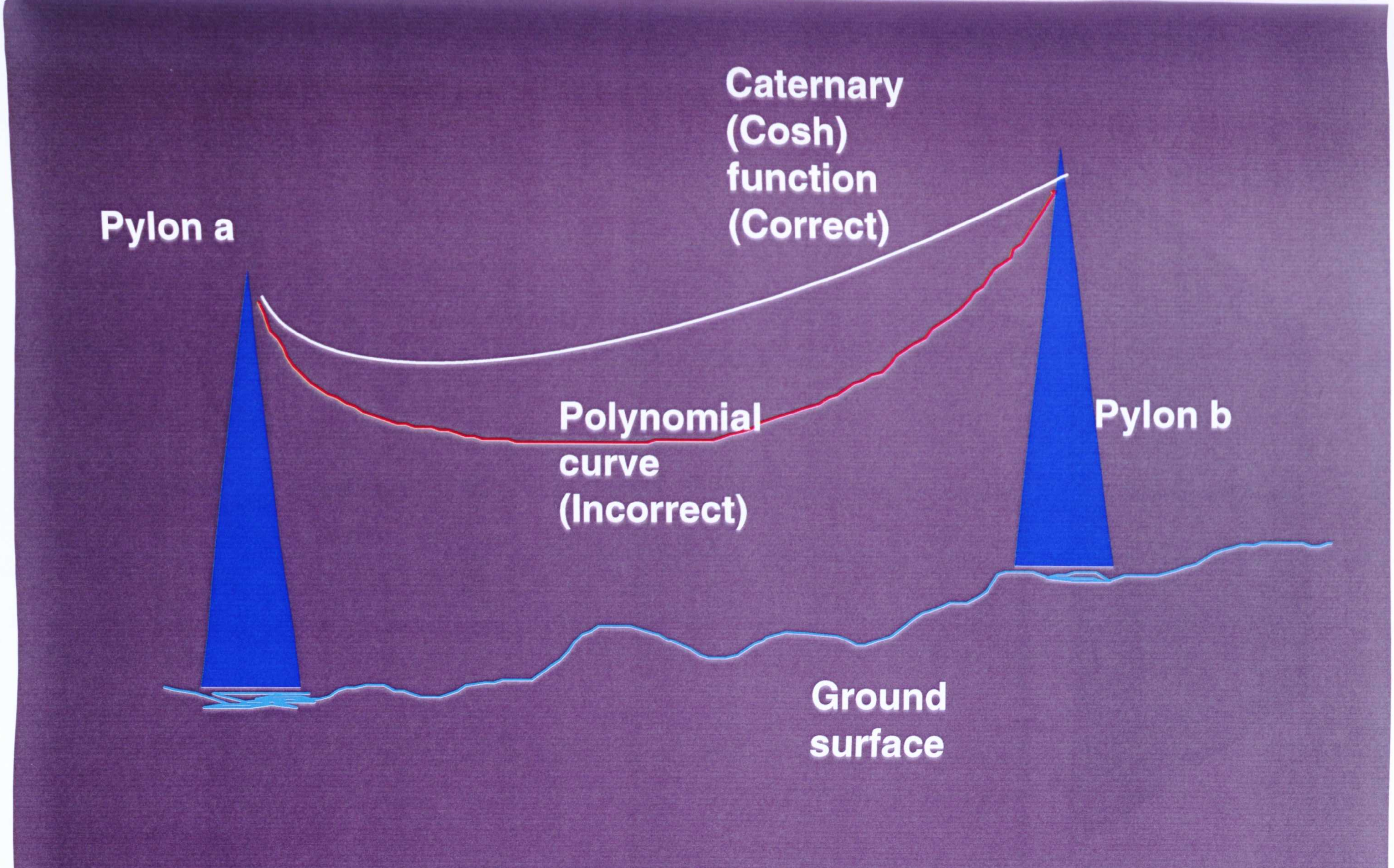


Fig. 8.18 Catenary functions for pylon towers

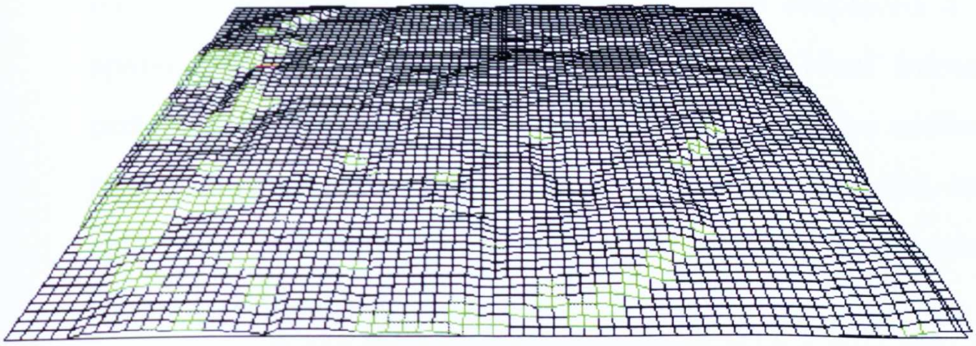


Figure 8.19 Resultant terrain surface before erosion

validate the whole of Geoforma - physical and human geography elements working in tandem. The exercise emplaced a relatively sparse settlement pattern, but created an rather 'ideal' infrastructure - certainly the density of roads and railways would be unlikely in this part of North Africa, although this was besides the point, as the road categories can simply be downgraded so that they match tracks, footpaths or goat-tracks.

The other major exercise - run over several days with several 'failed' attempts - eventually produced convincing topography and culture for Germany. These are shown in Figures 8.20 and 8.21, which represent a DTED format matrix for a user attempting to create maps of Germany (and viewing them in 3D to see progress), and Figures 4.11 and 4.12 in chapter four, which show the same thing for culture and a hydrology network for the same area. The maps were adjudged to be successful and were accepted by the sponsors as validation of the entire stage of the research, particularly since the DTMs of the areas were available in the correct formats (DTED and DFAD) on demand. It should be pointed out that some test maps (and failures) were created as it took many iterations to produce the sophisticated examples shown in the sequence of figures above (see chapter three for some test maps). The maps in all cases show the following desired results (or acceptance criteria):

- Settlements were in 'realistic' positions (e.g. not in lakes or on top of mountains)
- Roads of different categories were in realistic linkages and networks
- Railways followed realistic routes and networks
- Contours accurately described the DEM

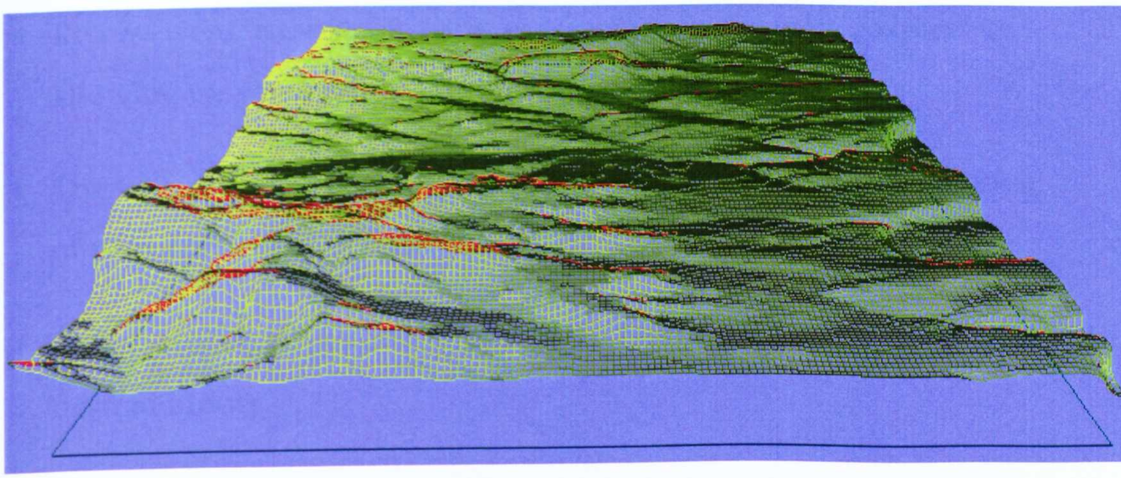


Figure 8.20 DTED matrix for 5 km area of Germany

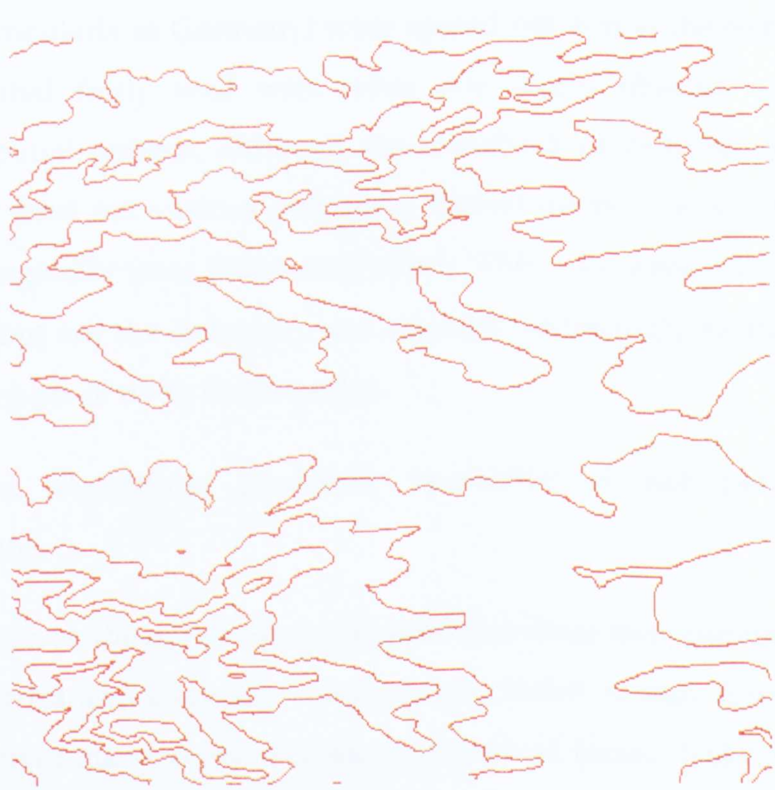


Figure 8.21 Contours for DTED file

- Rivers were consistent with the stream laws (see chapter 4) - allowing for some minor user post-processing
- There were no adverse or 'absurd' effects such as contours crossing or rivers not running downslope.
- General relief, slopes and 'grain' of the land were all consistent with desired inputs
- An 'overall' realism and quality was achieved that surpassed any previous exercise.
- Woods (particularly in Germany) were spread out across the terrain and correlated fairly well with what one might observe as a 'realistic' spatial pattern, although the drawback of creating only rectangular (and not various polygonal forms) tracts of woodland detracts marginally from the overall effect. This was noted and the algorithm (but not the software) was adjusted accordingly to allow simple polygons of up to twelve sides.
- Place name algorithms produced 'workable' if not perfect nomenclature.

On a personal level, the author was delighted that these two exercises - from North Africa and Germany - were so successful as they formed the culmination of many years of work. Synthesised terrain had come a long way from the eggbox topography used so avidly by the author to simulate intervisibility in the early 1980s.

Finally, Figure 8.22 illustrates some 'STICK' and 'WINGS' output - again using these subprograms from Geoforma, where the user is attempting to synthesise an area based on the Black Forest, near Germany. This was a step along the route to the 'final' coloured 2D output (maps). It must be stressed that many abortive or trial and

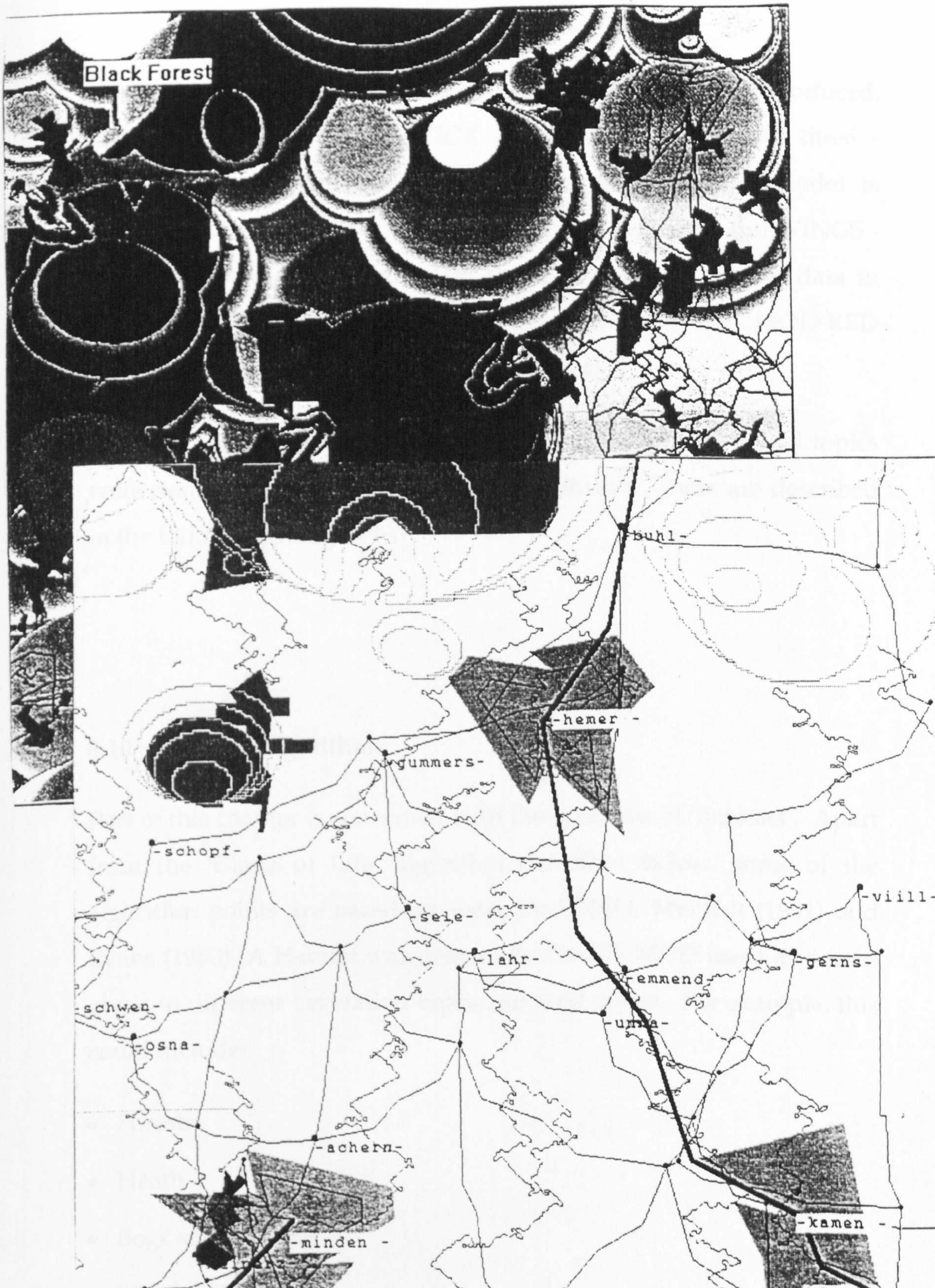


Figure 8.22 Trial attempt Using STICK and WINGS modules (example only)

error attempts were made before the quality maps could be produced. The subprograms such as STICK are described in chapter three - indeed the whole structure of Geoforma as a software model is described, with a diagram, in chapter three (note: STICK and WINGS - they are not acronyms - correlate elevation data and feature data in DTED and DFAD formats and are parts of the MOD-RED collaboration software initiated by the author).

After the successful exercises were completed, some additional topics were examined but not included in the software. These are described in the following paragraphs.

8.10 Habitat Algorithms

Part of this chapter is concerned with the synthesis of 'habitats'. Apart from the 'Game of Life' algorithm described below, some of the algorithm points are based on work by CSIRO, Mitchell (1991) and Evans (1980) A Habitat was defined by the UK MOD users as a term given to different vegetation types and land usage. For example, this could include:

- Forestry
- Heath
- Bogs and Marshes
- Meadow land
- Arable land
- Horticultural land
- Orchards and Vineyards

- Marsh and salt marsh
- Sand dunes

There are many other examples (e.g. mangrove swamps, industrial wasteland, radioactive zones etc. - the NATO DLMS system has a full and extensive list of such areas which can be incorporated into the culture file DFAD).

Currently, only forestry and bogs/marshes have been considered for inclusion in Geoforma and the synthesised terrain models as these have an obvious effect on intervisibility (weapon system simulations) and mobility of AFVs. However, some work was done in order to examine the possibility of employing habitats in the terrain model on a 'dial up' basis. The key advantage is that the software (Geoforma) had already been developed and it was seen initially as a simple task to augment the algorithms with habitats. The work was not carried out to the level of introducing it into the software but is reported here for completeness.

8.10.1 Terrain Analysis and algorithm development

The characteristics of real habitats to be reproduced in synthesised terrain are as follows:

- Total areal coverage - the percentage of the AOR to be covered by the habitat

- The distribution of total coverage into clustered blocks of different sizes

- The correlation of the habitat with underlying terrain characteristics like slopes, soil type, underlying geology, the relative position on a coastline or within a drainage system and prevailing weather/climatic conditions.

The first two points were thought to be covered under the parametric processes already described and therefore would form part of the terrain analysis. However the last point must observe certain 'rules' if a good correlation is to be achieved between the selected habitat and the underlying topography. For this reason a rules-based algorithm was selected. This allows conditions in the synthesised terrain AOR so that habitats can be 'matched'.

This can be checked in two ways. First, if the terrain has been faithfully synthesised and the correlation between inherent terrain characteristics and the attributes of particular habitats have been properly understood and applied, then the conditions of areal coverage and distribution over the synthesised terrain should be similar to the original terrain. The second check is a simple Boolean 'checklist' approach: bogs and marshes will tend not to form on slopes over 25 degrees (for example), and areas of supposed aridity would also not be expected to support bogs unless these were carefully juxtaposed in relation to drainage patterns. Equally, afforestation is unlikely on a rocky outcrop along an exposed coastline, above a local treeline altitude, or in high latitudes.

Returning to the terrain analysis, the areal coverage statistics derived from terrain analysis may be used both to check on the validity of the algorithms adopted and the fidelity of the underlying terrain. In cases where map analysis has not yielded all the necessary correlation data between habitat location and underlying terrain characteristics, then the areal coverage parameters may be used to condition and control the result of the (partial) rules-base algorithm.

8.10.2 Woodland algorithm and terrain analysis

Terrain analysis was carried out on maps to derive the areal coverage statistics of woodland or forests in the geographical regions to be synthesised. In addition, the terrain analysis provides a confirmation of the hypothesis for the regions considered (although different rules would apply elsewhere). The test area was based on the 1:25,000 UK OS sheet (Wales) for the Brecon Beacons (*Outdoor Leisure Sheets 12 (ISBN - 0-319-26062-3*). In this area, it was thought that determinism could be used (with care); forests tended to occupy either steep slopes not conducive for horticulture or most forms of agriculture, or areas of moorland above 500 m OD. In the higher areas a 'tree line' was identified, although this is more relevant in areas of higher relief where the tree line is a physical delimiter on woodland or afforestation. There appeared to be no realistic correlation between forests and soils, and for the test area in Wales some allowance must also be made of the fact that the AOR lies in a National Park, and this undoubtedly has an affect on the distribution of forests.

One useful parameter derived from the terrain analysis was the range of slope values over which forestry is likely - in other words there is a crude correlation between slope and forestry. The forestry or woodland algorithm operates on the principle of stepping through the digital elevation matrix (i.e. each gridded point in the DEM) and detecting slopes and altitudes within the range on which forests have been observed to occur. Forest habitats can then be created in these areas, with their boundaries defined either by obstacles such as cliffs, rivers, steep slopes etc., or simply on an 'average size' rule - once a certain forest size has been reached then it would be unrealistic to enlarge it further.

In order to compensate for the lack of knowledge about the underlying soil (in this case), and the subsequent lack of correlation between forests and soil types, a second pass through the DEM may be implemented. This checks that the areal coverage is in line with the sampled values and adjustments may be made to bring the forests within the bounds experienced in the real terrain observations. This second pass can also impose *rectilinear characteristics* (as many forests seem to be bounded by walls or field boundaries) observed in the original maps.

8.11 'Game of life' algorithm

Another, quite different algorithm can also be used in a more general case to 'seed and grow' forest habitats. The original 'game of life' was invented by John Horton Conway and is described by Gardiner (1970), Guy (1983), Albers (1994), and others. Using very simple rules, it describes the growth and decline of a population, concentrating on the 'automaton' balance between cell decay and cell exponential growth. The basic algorithm is thus: a live becomes a dead cell in the next time step if it has fewer than two or more than three live neighbours. In the first case, it dies of 'loneliness' (or lack of support); in the latter case it dies of overcrowding. If it has two or three live neighbours, it will remain alive. A dead cell becomes a live cell if it has exactly three live neighbours. These rules are completely deterministic, and a version was described for synthesised terrain vegetation in Griffin (1987), and was inspired (but not bounded) by a variation on the 'game of life' concept prevalent at that time, using tree instead of cells. The contemporary version involved a simple 'simulation' whereby respective populations of foxes and rabbits (for example) would flourish or decrease depending on food supplies as well as proximity. The growth approximated an epidemic curve (e.g. while the rabbits prospered and the foxes ate the rabbits both populations prospered) but went into sudden catastrophic decline beyond a certain rabbit population threshold. The forest algorithm used this idea, albeit crudely and in a different context for the synthesised terrain up to about 1992, where the simulation was based on the following simple algorithm steps:

- The users, by means of the main GUI, is given an option about whether woodlands or forests are to be synthesised, and if so what is the percentage of areal coverage for forests

- The user is also asked to select a number of seeding points, and whether these are to be placed manually by the user or are allocated by the system on a random basis.

- Each seeding point is mapped onto the AOR at a particular grid reference or Cartesian **(x,y,z)** position.

- Each seeding point 'infects' the point adjacent to it: **(x+1, y), (x-1, y), (x, y+1), (x, y-1)** and if necessary 'diagonal' points can also be seeded.

- The further growth for N number of passes depends on a weighting factor (where N can be allocated by trial and error to give the rough percentage area coverage) This in turn depends on purely deterministic factors, such as aspect (south and south-west slopes could give a high weighting factor); other terrain attributes such as steep angle slopes, outcrops, open water, stream channels, areas marked for non-afforestation (by deliberate encoding to take account of factors such as urban areas), whereas poor aspects and many other features might give low weighting factors.

The simulation was successful, but rather crude. It could be run so that the user could watch the growth or progress of the forests; interestingly the initial results were encouraging and the forests tended to 'flow' into valleys and shun hilltops. However, experience from the Hanover region of Germany (where the 1 (BR) Corps of the British Army had a massive presence during the 1980s and where the synthesised terrain at that time was needed for simulation exercises) showed that the local landowners tended to restrict woodland to hill summits - quite the reverse of the algorithm results. Therefore although successful, the algorithm could be negated by local or regional farming techniques, unless careful field validation was carried out. Fortunately the author spent considerable time with the Army in the Hanover region and took many hundreds of photographs to support the algorithms being developed. Also, it was possible to change the rules so that trees 'favoured' hill summits.

Figure 8.15 shows a spread of woodland tracts across 'Central Europe', where this algorithm is utilised, albeit without any obvious delimiters (coastline, cliffs or other features) to restrict the spatial distribution. The rectangular presentation aspect of the woodland noted above detracts slightly from the realism, although in compensation some woods have 'joined' to form more complex polygons.

8.12 Marsh/bog algorithm and terrain analysis

Terrain analysis confirmed the hypothesis that marshes and bogs tended to be located in flattish areas either side of as river in temperate or high temperate areas, typically where a number of streams flowed into a basin where hydrostatic equilibrium is reached before the basin encounters a state change into a lake. The terrain analysis also resulted in statistics of frequency of occurrence and areal coverage for marshes and bogs.

A basin detection module was encoded in Geoforma to identify potential lake basins within the original DEM. This was partly to help with the problem of 'walking' streams into *cul de sacs*, as described in a previous chapter. This information can be combined with a drainage model to detect basins where the channel link of streams with a Shreve order above a specified value have a gradient of less than a given amount. These areas are therefore candidates for marsh and bog habitats, although in some cases the lack of knowledge about soils and underlying geology prevents the rules-based algorithm from completing the process.

A second pass over the marsh/bog candidate areas within the AOR (i.e. by incrementing through the DEM grid points) allowed the bogs and marshes to be defined in a random way, so that these areas accorded with the coverage and location of observed results.

8.13 Conclusion of chapter

This chapter has described how the 'infrastructure' - the cultural, man-made and vegetation components of topography - can be treated and introduced into synthesised terrain models. The work was done in a somewhat 'enforced' manner admittedly because of the support (and pressure) from a sponsor, but even so the author was pleased with the range of topics covered and with the successful 'end-product' maps. The use of Central Place Theory and the algorithms aimed at 'sensible' settlement, road and railway networks are felt to have been satisfactorily achieved, even if simplification was inevitable. The placename algorithm was more ambitious, but at least it provides a starting point for more informed work in this area.

The two Geoforma exercises on upland and plateau regions - from North Africa and Germany (and Northern Europe) respectively - yielded particularly satisfactory results. However, the difficulties inherent in such work were brought home to the author while the human geography algorithms were being developed. For example, some subjects - such as place name synthesis work - would merit a major research project by themselves - and so it would be arrogant to claim that all the problems had been solved. Indeed , in many cases only the surface of the problem had been scratched, and much more work would be needed to make the algorithms sounder - let alone the software based on the algorithms.

In spite of this, the chapter reports on an interesting phase in the work, where the physical landscape could be made to 'work' - albeit in a deterministic manner - to help produce roads, railways and settlements. Detailed features such as pylons and catenary curves for power lines have also been examined, although it is freely acknowledged that there are many other such detailed features not in the scope of the study (e.g. factory chimneys, ditches, embankments, motorways, advertising hoardings etc.). Clearly much more work is required if true synthesised terrain 'human geography' is to attain a similar quality with regard to the physical or geomorphological algorithms. If such parity is desired then the human geography and culture will need a similar amount of investment in terms of research if it is to achieve similar levels of rigour and realism.

CHAPTER NINE METHODS OF VALIDATING SYNTHESISED TERRAIN

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Chapter Nine

Methods of Validating Synthesised Terrain

9.0 BACKGROUND

This chapter examines the ways in which synthetic or artificial terrain created throughout the programme of work can be validated or otherwise judged to be 'of worth'.

9.1 Overview

The word valid, according to Chambers Dictionary (1998) is defined thus: ***Sound; legally adequate, or efficacious; fulfilling all the necessary conditions . . . to confirm, substantiate and verify.*** Validation of something 'subjective' is a difficult area by its very nature: the act of synthesising terrain is by definition to produce an artificial landscape, and there are no known standards or criteria by which artificial digital landscapes may be assigned objective or even subjective value. Indeed, as far as the 'dial up' terrain modelling is concerned, the very parameters and baselines by which synthesised terrain may be created will - almost invariably - be 'reflected' in the final product DTM, thereby introducing an element of recursion and - one could argue - statistical unreliability.

9.2 Analogies and comparative validation

A simple analogy may be made with woven cloth made out of four colours. Whatever patterns are produced, a sample of the cloth, ranging from a few square centimetres to a group of individual stitches will naturally indicate the original colours even though from a distance red and blue (for example) map appear mauve. This is also an example of a 'self-fulfilling prophecy', since by using the colours one cannot but avoid seeing them close up, no matter what the distant patterns look like.

A more complex analogy is given as follows. Consider a situation where some music is composed based on a classical piece (such as one of the six works known collectively as the *Brandenburg Concertos* by JS Bach - for the sake of argument the *No. 3 in G Major*) as inspiration. Then let us suppose that the new composition 'borrows' the basic theme, sub-themes, melodies and ornamentation (details of style) from the original work, and uses the original collection of instruments in about the same balance. When the new composition is performed it is obvious to the audience from what source the original inspiration was drawn, yet the new piece may or may not be satisfying in its own right. Taking a sample of, say, 100 musically-proficient people from the imaginary audience, questionnaires are handed out with questions like "how much - in a range from 1 to 10 - did this new composition remind you of the Brandenburg Concerto No 3 in G Major?" An analysis of this essentially subjective survey might yield a high return: let us say that more than 70% of this imaginary sample audience were reminded strongly of the Brandenburg Concertos and this was found to be statistically meaningful. Further statistical analyses, based on a musical comparison (e.g. phrases, patterns etc.) might also yield a statistically significant correlation between the New Composition and the Brandenburg Concerto No. 3.

But what does this tell us? Is the composition 'better' or 'worse' for having been based on the original? A proportion of the audience might strongly agree or disagree. The point is comparing and contrasting the original and the derivation shows:

- There may be a quantitative relationship (e.g. a statistically significant correlation)

- That there may be a qualitative correlation (most of the audience thought that the derivation sounded like/reminded them/had copied the original).

However, the point really at issue is that neither of these exercises may be significant if the audience strongly liked (or strongly disliked) the derived piece. One might state that if the audience approved of the composition, then proving or disproving a quantitative or qualitative relationship is irrelevant: the audience like the piece and ***this is the only criterion that matters to the composer.***

Indeed, returning to real *versus* synthesised terrain in the STDRD programme of work (1994-1997), and the UMV project that preceded it chronologically (1983-1986 - but was not related), the mere fact that the sponsor (the equivalent of our imaginary audience) ***strongly liked*** the results of the synthesised terrain were enough in itself at that time; the terrain was adjudged 'geomorphologically-sensible' at the level to which it was intended (i.e. simulation and training models for people not trained in the earth sciences) and was therefore passed as 'fit for purpose'. To reinforce this, the people doing the work were paid accordingly. Therefore the synthesised terrain was passed as 'validated' and successfully negotiated the MOD's stringent Quality Assurance (QA) procedures. Under the strict interpretation of our term *Valid* the synthesised terrain generated during the 1990s (i.e. from this period) passes the test as being ***Sound; legally adequate, or efficacious; fulfilling all the necessary conditions.***

However, this chapter of the thesis attempts to go further than merely stamping an imaginary 'approved' stamp on a synthesised terrain DTM or synthesised map as 'fit for purpose' or just because the sponsor happens to like it. Although the subjective element of judgement is important (and might subconsciously override even geomorphologically-sensible examples in a certain context), there must be better, more convenient, rapid and acceptable methods of establishing the geographical integrity of a synthesised DTM. By 'geographical' fellow Earth Scientists are asked to indulge the author for including, by implication, inputs from all relevant branches of geomorphology as well as geology, climatology and hydrology. Human geography and 'culture', is of course also represented, although no expertise is claimed in this field. The following paragraphs discuss this thread of research, although it must be stressed that there is no 'absolute' - like so many things in geomorphology - the proximity to truth is merely a substitution for increasing probability.

Even so, the author reasoned that there must be ways by which the results of synthesised terrain can be validated, not just both qualitatively and quantitatively, but practically. Subjecting each synthesised terrain model to an analysis process longer than the creation process somewhat defeats the object unless the synthesised terrain model in question is a test case. This being so, and drawing on the musical analogy, it is possible to divide the question of whether a model is 'fit for purpose' into qualitative and quantitative methods. As a result, this chapter sets out to discuss these methods, which are divided into qualitative and quantitative approaches.

9.2.1 Quantitative Methods using synthesised terrain maps

The quantitative methods have already been partially established in chapter three; they include techniques such as statistical analyses of certain parameters, including mean height, mean distance between summits or drainage density, and many others. There is no reason why the synthesised terrain output cannot be treated to an identical parametric analysis, in order to compare it with the original real world

DTM or AOR. The principle that any results (output) may simply reflect the input parameters can be used in more than one way. For example, one might expect to find such a reflection; this itself is a kind of measure of integrity; like our cloth analogy it would be anathema to discover a primary thread coloration that was not originally one of the four threads. To continue, this approach throws up the philosophical question 'are we really synthesising terrain at all or merely re-mixing it?'. At the other end of the spectrum, if the reflection (of input parameters) is not evident, then this too must be addressed. In the cloth analogy this would be equivalent to finding no evidence of one or more primary coloration threads. It is hard to know which scenario is worse for the imaginary cloth inspector!

The quantitative approach involves the examination of various sets of values by which the synthesised terrain created and described in previous chapters (and similar terrain created by similar methods) may be adjudged to be 'fit for purpose'. Much of this stems from the original reasoning behind wishing to synthesise terrain, and the value attached to such activities in different areas of utilisation. In other words, one must put the validation tests into context. The various concepts of scale, resolution, accuracy, and terrain classification must also be taken into account, along with the other fundamental terms, concepts and techniques already seen, in order to 'make sense' of the intrinsic value of synthesised terrain.

The quantitative approach uses a number of techniques. First, a brief series of exercises were carried out using estimates and measurements of such features as slope (mean, maximum, type etc.), distance between summits, drainage characteristics etc. The results were compared with the original set gathered for the two regions (North Africa and North Europe, as well as a brief exercise from an area in South West England). The figures represent the estimated comparison, expressed in percentage terms, between the original set and an estimated subset from the synthesised terrain based on the original. One would expect a reasonably high correlation, but there are reasons why this is not so high as might be predicted (this explained in the following paragraphs). Correlation techniques were not used because of the 'error' factor involved in collecting the data - it was felt that a simple arithmetic count would be sufficient (for example if the original sample for North Africa had a mean slope of 15.2 degrees, and the synthesised terrain sample of 'imaginary North Africa' appeared to lie between 10 and 17 degrees, then the percentage was calculated by taking the difference between the means (therefore (10 + 17)/2 = 13.2, which is 86.84% of 15.2, or 87% if rounded up).

The results are shown in table 9.1:

AOR/sample	North Africa	North Europe	SW England
Attempt 1	87%	82%	91%
Attempt 2	67%	70%	81%

Table 9.1 Results of parameter comparison estimation exercise

The results show two attempts for each of the three areas, the first attempt is before the river erosion model was run, whereas the second attempt was after the river erosion model had been instantiated. The results show, predictably, a high correlation, but this is expected and is a validation of the closeness of fit to the real world AOR rather than to any sense of 'validity' *per se*. However, the values decrease after the river algorithm was run, since this changed the landscape away from the original but towards (what is hoped) a very realistic synthesised terrain model. North Africa was more affected, possibly because the indexes for relief were more significant and the river algorithm 'knocked off the corners' somewhat more than at the other areas.

Finally, it must be said that the parameter approach - in a sense - already has allowed for fluvial erosion, so there is an enigmatic quality in 'modelling what is already there'. No human geography features were included in this relatively simple exercise. Taken together it is felt that the methods are adequate in 'validating' the terrain, since the standards and reasons for validation may be so widely different.

9.2.2 Other Quantitative Methods: Discussion

This area of possible validation is perhaps one of the most difficult to argue. Consider, for example, a carefully derived data set of synthesised terrain based on the study and classification of a real-world area, such as Dartmoor (see Figure 6.6 in chapter six). The synthesised terrain output would (ideally) look like Dartmoor, and would have statistical results that compare favourably with the parameters that describe real Dartmoor. This by itself is not validation but it is step on the way. However, one could argue that the statistics are self-sustaining and that they have been automatically 'built-in' to the synthetic landscape, since the artificial Dartmoor is really only a rehashed or remixed version of the real Dartmoor. Therefore, in remaining faithful to key criteria such as mean slope, average distance between summits, average height, stream patterns etc., the statistics sampled from 'real Dartmoor' will - naturally - force the 'synthetic Dartmoor' to be similar, within any given probability test (e.g. Student T-test etc.). Yet this in itself is not real validation that the synthetic terrain is 'of worth', it is merely confirmation that the output has faithfully produced a distorted 'fairy tale' Dartmoor. How can this apparent paradox be resolved?

At a detailed level, simple control of features is relatively easier to validate. An example was given in chapter three, where 'unrealistic' slopes - or slopes that did not conform to the area of the world being modelled - could be controlled either by setting limits that do not compromise the terrain appearance or by providing warning messages to the user. The limits are set by allowing the user an agreed 'degree of freedom' - say 10% plus or minus whatever parameter is being manipulated. Thus if a slope becomes 10% greater than the setpoint, an error message can be made to appear, or the user can be prohibited from undertaking the action (i.e. the 'commit' is not allowed) or warning messages can be issued.

9.3 Qualitative Approach

9.3.1 Justifications

Whatever the reasons for the project, all the justifications for validating DTMs rest on the fact that the artificial terrain has satisfied some appropriate criteria for 'realism' or validation processes (referred to generically as lying within a 'realism envelope') in each case. These 'validation criterion sets' can be grouped as follows into broad areas, which can be examined both quantitatively and qualitatively:

- Satisfaction of a stated requirement regardless of the statistical, physical and presentation aspects of the terrain created
- The perceived 'realism' of synthetic terrain according to requirements or a given 'starting point'
- The perceived 'realism' of synthetic terrain according to the desire to model a real world area or region
- The statistical accuracy of a synthesised product, according to stated requirements, limits, boundaries and attributes

- Some other objective or subjective criterion

- A combination of any of the above

9.3.2 Satisfaction of stated requirements

This validation path lays out the 'goodness of fit' according to given requirements.

The perceived 'realism' of synthetic terrain according to requirements or a given 'starting point'

This requirement simply demands realistic-looking terrain. The user (whether a flight simulator user, a military commander, an AFV driver or a commercial landscape company) would require 'realistic' looking terrain. They would expect landforms and rivers to look real to the point that they may as well be real. They do not want alien-planets, spires or inverted towers - they require a DTM that, for their purposes - *may as well be real.* This specification might have a detailed theme, such as 'produce undulating terrain in order to engage a moving target that is constantly disappearing from view and then re-appearing' - indeed such intervisibility studies have been carried out at Fort Halstead (now DERA), in Kent, since the 1970s, when the Warsaw Pact had a massive preponderance of armoured vehicles and NATO was heavily outnumbered (Hackett 1973). More rigorous specifications might require coastal DTMs (for amphibious landings), deserts, tundra (to simulate northern Scandinavia) and so-on.

The perceived 'realism' of synthetic terrain according to the desire to model a real world area or region

It has been stated that the desire to model a real world region has been one of the key themes running through the research. This is principally because of the Army, who wanted to provide simulation s for combat or driving AFVs (such as tanks) over 'familiar' ground, like the UK and Germany, but also to have the facility to model potentially hostile areas where real operations might have to take place. If, for example, the British Army was given a week to train for (hypothetical purposes only) an area in North Africa, it might be that there are maps available but no DTMs - certainly not at the level of detail and resolution required by an AFV driver or navigator. Therefore, the only way of providing such a DTM, that looks real and has the landforms of the region likely to be encountered (Wadis, desert, bare rock pavements etc.) is to carry out a rapid parametric analysis and invoke Geoforma to produce the DTMs. The alternative would be dangerous air activity over the hostile region, and a photogrammetry process that might take weeks.

9.4 Validation according to composite and other methods

9.4.1 Qualitative Methods using preference models

Qualitative methods are essentially subjective. They are not normally associated with statistical rigour or probabilistic analyses (although there is no reason why they cannot be combined with statistical analyses). Some work has been done on 'landscape preference models' by Wherrett (1999, 2000). Wherrett (2000) examined predictive landscape preference models, itself based on 'psychophysics' - defined as the study of measurement theory and procedure which attempts to relate environmental stimuli to human sensations, perceptions and judgements (Hull *et al*, 1984, p.1084). Wherret also used codes to represent particular landforms, following work by Shafer (1969, Shafer and Brush 1977 and Brush 1981) but the obvious leap into the world of terrain classification and evaluation is - surprisingly - not made. It may be that the authors mentioned were simply not aware of terrain evaluation methods.

Wherrett's work helps rank landscapes on various factors. She found that the most important predictors of visual landscape preference were found to be complexity, coherence (including colour), the presence or absence of water and mountainous terrain. When one thinks simply of a range of well known holiday resorts they include features such as mountains, hill, lakes and rivers scenery, beaches, etc. - recreation tends to be correlated with places which are aesthetically pleasing and which provide opportunities for activities (walking, water sports, fishing, etc.). Wherrett's work is different in that she attempted to quantify factors related to landscape perception and appreciation, using the internet as a communication and GUI tool. Had circumstances permitted similar internet-based surveys could have been postulated for the synthesised terrain produced in this thesis, although this was beyond the scope of the research (and Wherrett's work is quite recent so the organisational aspects would have been difficult to arrange for this thesis).

A factor in the synthesised terrain involves 'preference' or 'beauty' - the terrain was patently not simulated for this reason - but if the resultant 3D views look 'attractive' this can help add to the realism. Indeed many observers involved in the work pointed out particular landscapes and expressed appreciation of the 'beauty' of some of the rendered 3D pictures. One might speculate on the reaction if 'nightmare alien fractal landscapes' were presented to a sample - especially if Wherrett had included some synthesised or unearthly scenes in her study. There may be a relationship between a degree of natural beauty in a landscape and perceived realism - although it is pointed out that the author has no evidence to support this. Landscape assessment has been established for some time (Appleton 1975, Arthur *et al* 1977, Dearden 1980) and recently the advantages of using the internet to collect data - in that it avoids hard copy medium, face-to-face contact etc. - has been exploited by Bishop (1997) and of course

Wherrett (1999, 2000). The motivation for much of the work is related to land use and the types of scenery people would prefer to see. One can imagine that agencies 're-landscaping' an area of decay due to mineral extraction or mining would value such information. Interestingly, synthesised terrain can also play a part and it is perhaps unfortunate that although some simulation is included in the general area of work (Bishop and Leahy 1989) the closest the authors mentioned above come to synthesised terrain is about the level of 'artists impressions' or specially constructed landform 'vectors' as 2D pictures (see Wherrett 2000 p. 86).

9.4.2 Methods using a survey to validate synthesised terrain

Leaving aside studies of landscape appreciation and preference, at its basic level, a synthesised DTM can be presented by means of maps and 3D pictures at various scales, orientations, renderings and so-on. This can be shown to 'end users' - i.e. those who will be using the DTM for simulations or training among other reasons - for comment. This effectively mixes qualitative with quantitative methods. To establish some rigour behind the comments, a questionnaire was constructed for the purpose and used with a proposed sample of 50 people connected with one of the military training projects in the mid-1990s. The questionnaire (reconstructed by the bullet points below) rates answers on an ordinal scale, so that four questions have ratings from 1 to 10. The four areas, posed as questions, were:

1. **Realism as a landscape in a general sense**

2. **Realism as a model of a 'real world region' (physiographic fit)**

3. **Fitness for purpose (acceptability)**

4. **Aesthetically pleasing (on a scale 1 to 10)**

The people comprising the sample were also asked for their opinions about:

- **What are the most striking features?**
- **Are you impressed with the landscape?**
- **What are your general comments (free expression)?**

The ratings for question 4 are as follows:

1 Not realistic at all (complete disagreement)

2 Poor realism

3 Poor to fair realism

4 Fair Realism

5 Fair to good realism

6 Good realism

7 Good to Very Good realism

8 Very Good realism

9 Very Good to excellent realism

10 Excellent Realism (complete agreement)

First the study ended before the sample could be completed and for security reasons the results are not presented. However, the lessons learnt from the sample work was that it would be better to present the maps to a mix of people (i.e. those who were connected with maps and those who were not but were cartographically literate). Also, the sample did not need to be so big as some obvious trends were emerging. One trend was that if the subject worked in a mapping or *simulation department in MOD and were aware that the map was* synthesised, then the level of rigour would change - *it was found that* the sample group would be preconditioned to respond either *very positively* or *very negatively.*

Initially, with a group of 10 different people, a selection of 10 DTMs were printed out as 3D views. The people were taken from a cross-section of IT workers at Oracle Corporation UK Limited, and none of the people knew anything about the project, none were personally known to the author, and none knew anything about synthesised terrain until it was explained to them in outline. However, this had the effect of ruining the exercise because the sample either were confused by the concept of synthesised terrain, or were impressed to the point where they wished to know how the maps had been created. So explaining about synthesised terrain before the exercise was attempted meant that the whole sampling process had to be abandoned, simply because most of the sample already knew that they were being shown a synthesised terrain map and answered in a way that was certainly constrained and may have even been designed (however subconsciously) to 'please' the author. This in itself is interesting, but it was thought to be better to avoid the subject of synthesised terrain altogether unless, for some reason, the person asked if the map 'was real' (which did not happen).

Finally, it was decided not to mention synthesised terrain until after the questions (or as part of one of the questions). This was an important decision because by declaring the techniques or explaining what synthesised terrain is all about was found to affect the answers given. The 'freshness' of a sample of only 10 people where the map is shown to the interviewees without explanation (and they read the title 'North Africa' or 'North Europe' so they had no idea about synthesised terrain) was found to be satisfactory, and although statistically a sample of N > 50 may have been preferable, the author was sufficiently convinced that the results would have been no different. The maps used were the two from North Europe (Figures 8.14 to 8.17) and the single map from North Africa. The results are shown in Table 9.2.

This sample (with the results shown in the table) was in the 18 to 65 age group, 7 males and 3 females (N = 10). This sample were not asked the four questions numbered 1 to 4 above, but instead were asked three questions:

- What are the most striking features? Anything wrong or interesting?
- Are you impressed with the landscape - is it a 'normal' map?

The sample group were *then* told that the maps were totally artificial and portrayed some completely imaginary area that ***looks*** like North Africa or Northern Europe. This took some time, and the author also showed early, primitive attempts to model 3D synthetic landscapes to demonstrate the non-trivial nature of the task. The sample group were also asked to give a mark from 1 to 10 (as shown above) for realism, and asked the final question:

- What are your general comments (free expression) given that you have been told that this is synthesised terrain?

The results are shown in Table 9.2 (where the number in the sample is listed 1 to 10 and the realism factor is placed accordingly)

No	1	2	3	4	5	6	7	8	9	10
Realism	9	8	8	9	10	8	7	9	8	8

Table 9.2 Results of final, adjusted questionnaire for synthesised terrain

It can be seen that a very high level of realism has been assigned to both sets of maps, even though the sample were encouraged to be honest. The lowest number was 7 (Good to Very Good realism)

Typical comments were:

- Place names were too small to see without a magnifying glass. This is a partially function of the necessity of printing the maps on A4 when they are at a scale of 1:500,000) - sample numbers 3, 4 and 9

- Morocco possibly had too many watercourses for a supposedly arid area (3 and 7).

- The woodland was perhaps too prolific and too 'rectangular' in Northern Europe maps (4 and 6)

- No-one questioned the settlement on top of a hill in the SW corner of the North Africa map (although this was meant to represent an ancient fortified hilltop town).

- More marine 3D pictures or maps were requested (this was an acknowledged weakness).

The weakness of such an exercise is obvious:

- The sample is too small for statistical validity although it does give an indication. However, the large number of interviews already conducted - although not shown here - gave the author the confidence that they results would be similar whether 1000 people were asked, although this is of course an opinion.

- All the participants were relatively well educated - this may have affected their perception. It is possible that the concept of synthesised terrain is too novel for some people to make value judgements.

- One person may have guessed as the author's research may be known to some of the sample
- Some may have given the answer they thought was desired, and not have been 'objective' for capricious or other unfathomable reasons, even though the author implored them to be honest. However. while this is unlikely, it should be mentioned.

The exercise was repeated with another 27 people, this time from an area in the author's place of work where he is not so well known to his colleagues. This had the advantage of increasing the statistical significance of the sample, but presented new problems in that the sample was less reliable as the people were not so co-operative (as the people were busy). However, similar results were gathered (i.e. out of an incomplete sample of 27 (the author attempted to reach 40+ people but was dissuaded by the management) the lowest realism factor was still 7 and, although this exercise was 'statistically questionable' there appeared to be the beginnings of a normal distribution (with 7 and 10 as the outliers). The sample was abandoned as it seemed pointless to persist with something that is virtually self-evident. Many of the people were busy, as mentioned, and some gave flippant answers to bring the questions to a conclusion. That is why the earlier N=10 sample in Table 9.2 is felt to be valuable - all the participants took their time and there was felt to be a high level of veracity. Also, the exercise in itself is based on subject answers using an ordinal scale - there is no point is assigning too much statistical worth as a result. Having said this, this particular attempt to validate the maps was satisfactory, and some people even refused to believe that the maps had been synthesised to the level claimed. Moreover, all of the people commented that they could see a usefulness for such synthesised terrain modelling (usually as motion picture or arcade game special effects). Interestingly, cost-effectiveness (as compared to acquiring real DTMs through remote sensing or photogrammetry) was not discussed.

Although the whole exercise was moving into the realms of perception and therefore areas far beyond the author's training and experience, the author had now asked over 100 people (even though only 10 are represented 'formally') and the response was in every case can be paraphrased thus - without exception - ***'the synthesised terrain map could have easily been real - I was fooled and therefore it has a very high 'realism factor'***. It would have been educational to repeat the tests with geomorphology students, but this simply was beyond the resources of the project.

Such tests could be a useful future exercise for undergraduates; giving them a good synthesised terrain view, a poor synthesised terrain view and a real terrain view would be interesting with a meaningful sample (e.g. 100 or more).

9.5 Summary of the chapter

This chapter has examined ways by which the synthesised terrain products can be validated by using both quantitative and qualitative methods. The following points are made:

- Synthesised terrain has come a long way from the 'eggbox' topography to the composite maps shown in this thesis.
- Synthesised terrain is demonstrably cost-effective for certain applications and may be used as a teaching or demonstration medium.
- It is difficult - perhaps impossible - to validate synthesised terrain by any extremely rigorous, 'watertight' or meaningful method.

- Quantitative and Qualitative tests show promise, but there are objections to both. The analogy with 'mixed up music' applies to the parameter-based synthesised terrain, while even the most rigorous attempts at comparing statistical results from original 'real' terrain and synthesised terrain merely confirm that a relationship exists where it would be strange if one did not (since one is derived from the other).

- At least the geomorphological models (such as the stream laws) built into the Geoforma output are at least moving towards a new level of realism. No other work or paper yet seen in the literature (or at a web site) purports to come close to such realism

- The 'realism' associated with fractals or FFT can be seen to be of quite a different order from the 'super-realism' depicted in some of the maps shown in this thesis.

- Current landscape preference work is useful in helping phrase questionnaires about the realism of synthesised terrain.

- A small 'true' sample, and two aborted samples all produced acclaim for the realism (and by implication the validation) of the maps

- Some MOD users mistook Geoforma maps for computer print-outs of TPCs, sometimes with amusing consequences (as in the case where one junior officer gave a short account of his holiday in a fictional Geoforma-created area, mistaking it for the area east of Hanover). This is circumstantial but it adds to the weight of evidence.

- Synthesised terrain based on 'dial-up' and parameterisation exercises has the nagging feeling that it is really just holding up a mirror to a real map. However, the process-response models of coastline and rivers, plus the human geography, help to stabilise this feeling and the compound effect appears to be satisfactory

- The MOD sponsors agreed to pay for the output, so by their strict QA measures the synthesised terrain must be fit for purpose and - *by implication* - validated.

- New, better methods hopefully will be *developed to give* synthesised terrain a set of 'standardised' directives for validation or realism. This is perhaps a pipe dream but it is worth mentioning, especially as Wherrett (2000) and others are already looking rigorously at similar aspects of real terrain and are on a 'parallel course'.

CHAPTER TEN CONCLUSION

Chapter Ten Conclusion

10.1 Background

This chapter provides a conclusion to the thesis. Within this general objective, the chapter strives to provide three roles:

- It provides a summing up of the thesis, with the advantages, strengths, weaknesses, and potential opportunities of the work seen with the benefit of hindsight and at a high level

- It provides the reader with a suitably-considered end to the thesis and to the research work described therein

- It outlines some of the future work that could be done, as well as some of the possibilities that yet await the exponents of sophisticated synthesised terrain models, for whatever branch of the earth or life sciences they represent

10.2 Summary of the thesis: general statement of achievement

It has been demonstrated that it is possible to produce convincing and functionally-viable models of digital synthesised terrain with a reasonable element of geomorphological integrity and general geographical acceptability. This can be done using an interactive GUI system with some rudimentary 'intelligence' in order to filter what is 'good' and what is not. In order to achieve this, the work has required, in general terms, the following:

- A reason to synthesise terrain (e.g. academic research or a formal requirement such as military simulation)

- Some geomorphological background for the physical landscapes
- Awareness of terrain evaluation/classification techniques and the different physiographic constraints imposed by selected 'real world' areas if these are to be used as templates
- Awareness of data models, databases and formats
- Immersion in the genre of DTMs, DEMs and GIS technique
- Ability to command a significant amount of information technology support
- Awareness and application of statistics and mathematics, including fractals
- Awareness of the earth sciences generally (geology, human geography, cartography) and the techniques, limitations and literature associated with these areas
- Ability to write algorithms advanced enough to be functionally useful but practical enough to be encoded within the architecture of Geoforma or whatever software system is being used.

10.3 Multi-disciplinary nature of the work: a necessity

The points made above show the overlapping and multi-disciplinary nature of synthesised terrain modelling. It is perhaps at first glance surprising that more work has not been done in this fascinating area, particularly given the simple alternative presented by synthesised terrain models on the one hand and the cost and unavailability of real world terrain models (from simple DEMs through to digital map facsimiles) on the other. This question is answered partly by considering the list of requirements above; to produce synthesised terrain one must either establish it as a subject in its own right, to be taught as a discipline in universities, or form a team of geomorphologists, geologists, geographers, computer scientists and mathematicians in order to solve the problems encountered. Since the former was never an option available to the author, and is in any case unlikely for the moment, the author had to resort to the alternative, which meant embracing and undertaking a multi-disciplinary research project. Fortunately, geographers tend to be relatively numerate and the author is employed as a professional IT consultant; nevertheless he is deeply grateful for the mathematicians, academics and cartographers who have helped, and who have been credited and acknowledged when appropriate throughout this thesis. Figure 10.1 shows an impression of the multidisciplinary nature of this research work leading to the thesis.

Therefore one signal conclusion of this thesis is that while the work has benefited from being driven by various MOD projects, this has also constrained the amount of geomorphological research that the author was allowed to undertake. Thus a balance has been achieved; on the one hand just enough geomorphological input (and human geography input where necessary) has been allowed to make the terrain 'geomorphologically viable' or realistic, whereas the academic research has, by necessity, sometimes been conducted by the author outside the remit (and resources) of the various projects. Regrettably, some important works (e.g. Rodriguez-Iturbe and Rinaldo (1997) and McClean and Evans (2000)) were published just as the algorithms and the coding was finished - such works are discussed in the text for relevance but due to the time scale of the work they could have no real impact on the PhD results. However it is not felt that any major contradictions would have arisen - rather the opposite - and such works would have underpinned the basic premise of the thesis that fractals have their use in geomorphological research (even though they are no panacea).

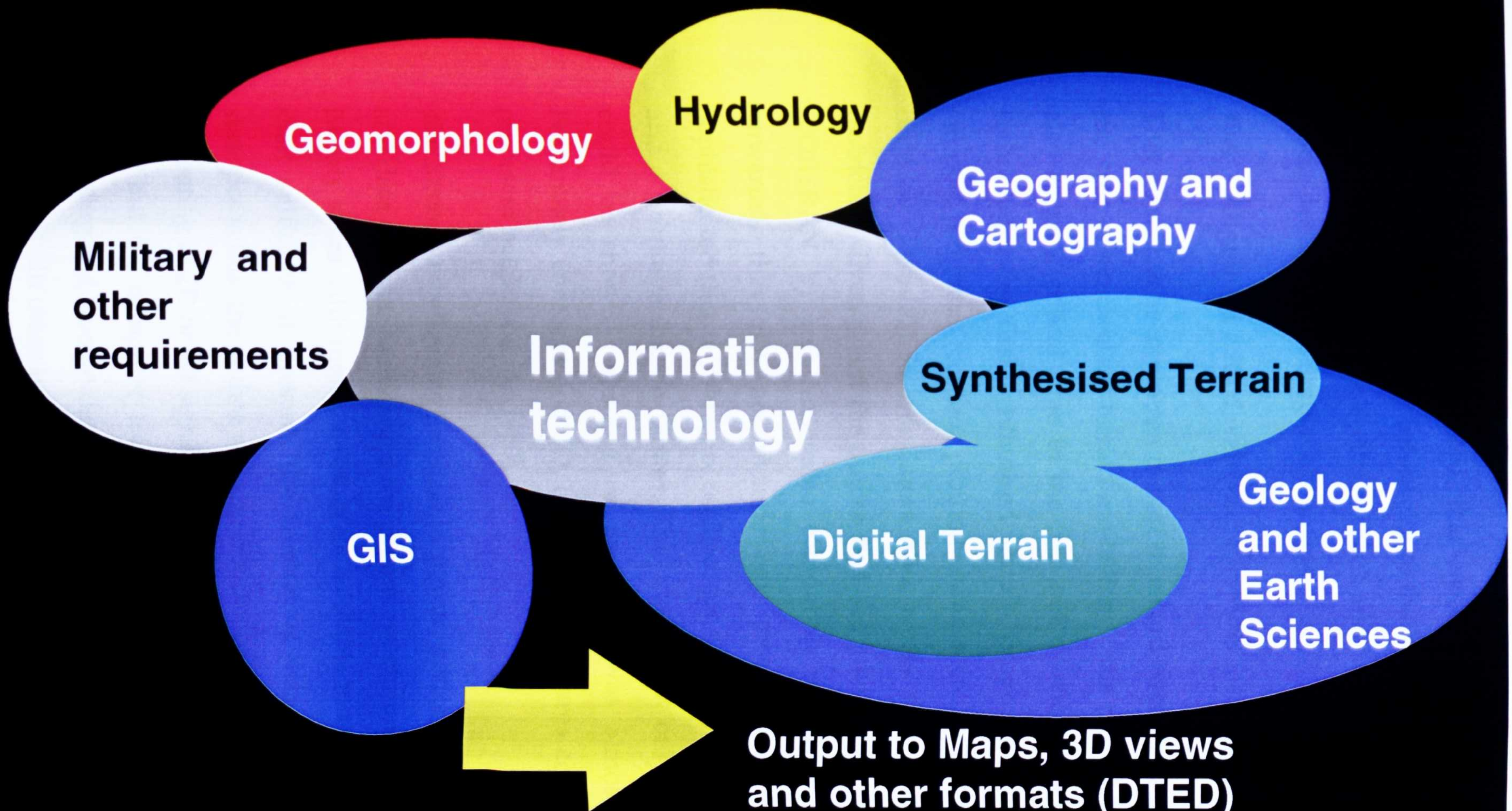

Fig. 10.1 **Overlapping Disciplines in thesis work**

Finally, it should be noted that synthesised terrain was being researched by the author before any of the MOD projects were started; it is original geomorphological research and was harnessed to projects, where necessary, for mutual advantage.

10.4 Alignment with developing computer technology

This thesis has been written in part to record over 20 years of work in the area of synthesised terrain modelling. This period, interestingly, also spans a critical time in the use and development of computer technology; the first synthesised terrain programs were in reality support programs (contour plotting routines etc.) written in machine code on Texas TI-58 calculators and access to a mainframe was restricted. Even when the author had the luxury of a 3GL compiler (FORTRAN V) and reasonable computing resources (from 1983 onwards), they did not include any presentation devices more sophisticated than a Tektronix oscilloscope adapted for vector plotting and a primitive inkpen plotter. This meant that only vectors (lines) could be shown - shading or rendering was almost impossible. Fortunately contours and 3D 'cheesecloth' pictures could be used to represent height (Griffin 1980).

The almost unbelievable increase in power, performance, functionally and data volumes has enabled the general revolution in IT over the last twenty years. Although the resources available to the author are more than sufficient at present, the frustrating conclusion of all these statistics is this: the author was capable of digitising, manipulating and presenting in 2D or 3D significantly large or complex data sets prior to 1985, but the computer technology (particularly the relative cost of processing and storage data sets) was insufficient until the late 1980s - early 1990s. In other words there has been an inconvenient mismatch; what was *theoretically* possible in the 1980s simply had to wait for technology to catch up before it became *practically* possible.

Therefore some of the work presented in this thesis existed as a theoretical exercise, since the facilities did not exist to implement them. Few GIS products were available at this time as the limitations were universal - only a few happy institutions could overcome such limitations (DARPA and MIT spring to mind) and even they were affected. More significant, the synthesised terrain work was tightly controlled by the MOD, which was reasonable enough since they were paying for some of the work. The author secured permission to pursue the work in his own time, and has been fortunate in that low security classifications and the constant resurrection of synthesised terrain across various MOD projects has kept the work moving towards the triumphant production and use of the Geoforma suite; a 'product' quite unthinkable in 1979.

Naturally the MOD requirements also constrained the synthesised terrain work towards military applications; it was only in the last 5 years that the military element has been played down to the extent that this thesis could be written, and - perhaps more importantly - some of the author's hitherto stifled geomorphological theories could be resurrected and built into a 'customised' model of Geoforma. Nevertheless, the author is grateful to the people with vision at MOD who were kind enough to enable the work to be published - see Griffin (1987) and Appendix A.

10.5 Observations on surprising or interesting results encountered

One complete surprise to the author during the latter stages of the research was the fact that the cherished process-response models (beloved of the author because they were rooted in geomorphological theory) were, in effect, somewhat 'toothless' without a decent 'primitive' land surface on which to operate. To explain this briefly: it is all very well flowing rivers down a simulated planar slope, but this is not how the real world operates. Also, using planar surfaces without terrain evaluation techniques (the choice of the Vicksburg and Natick methods and the parametric analysis) would deny the user the important functionality of being able to 'dial up' terrain from real world areas using appropriate maps.

This discovery seemed at the time to be a body blow to the work; yet it underlines three important lessons in research:

- Treasured or long-held assumptions are often wrong
- One can learn from ones' mistakes and must not be afraid to admit them and continue developing in the correct direction
- Even 'experts' in their field can have the humbling experience of their mistakes pointed out to them by 'non-experts'

The fact that phasing the synthesised terrain so that the geomorphological 'treatment' was almost incidental was at first galling, but it makes sense, and inexorably produced a better model where the geomorphological input was just as important - it just became applied at a different time and with a different emphasis. The author is grateful to Bob Privett for pointing this out and for making the case for 'multiple phase terrain processing' so eloquently. This seems obvious with the benefit of hindsight, but at the time the author was convinced that terrain evaluation was simply an enhancement that could be added to a process-built landscape - not the other way round.

Philosophically, of course, there is never a 'start point landscape' - even emerging marine planation surfaces are hardly pristine 'table tops' across which rivers 'magically begin to flow'. The 'chicken and egg' argument applies *par excellence* to synthesised terrain as it does in the real world, as it is hoped this thesis has demonstrated.

10.6 Validation

The previous chapter showed the ways in which synthetic or artificial terrain can be validated or otherwise judged to be 'of worth'. Whatever approach is taken, two overriding factors have emerged time and again throughout the years during which this study was conducted:

- Synthesised terrain (once a method of producing it has been established) is cheaper to produce than real terrain of equivalent *resolution and probably* always will be, even allowing for technology improvements in the Lidar *field*.

- The synthesised terrain models produced, whatever their geomorphological or general shortcomings, can be deemed 'fit for purpose' simply because they have been utilised successfully and extensively (mainly in DTED and DFAD formats) by military users. This is not necessarily rigorous enough, as chapter 9 explained, but it is difficult to gainsay.

- The synthesised terrain 'looks' realistic, and internally it 'obeys' certain geomorphological and geographical laws and principles. This is an improvement on most terrain synthesis attempts, few of which include geomorphological inputs and those that do maintain geomorphological theories do not appear to have the breadth of the 'generic' approach.

10.6.1 Weaknesses

The weaknesses of synthesised terrain are obvious and have never been disguised: synthesised terrain is of course not real, and making it seem real by using parametric analysis is a major undertaking, as the research that underpins this thesis demonstrates. Indeed, one could argue that only the 'surface has been scratched' and that far more could be done to model the landscape with more realism. For example, many landscapes are not represented in this thesis, notably arid areas, limestone (karstic) areas, 'classic' glaciation features, tropical environments and many more. And this is just at the physical level - the work on settlement, infrastructure and human geography deserves a thesis to itself. Finally, only two diagrams were permitted in the chapter on coastal features and this is an acknowledged (if explicable) weakness.

10.6.2 Strengths

The strengths have already been noted; it is enough in itself to synthesise geomorphological viable terrain for academic and research purposes. This original research has demonstrably pushed the boundaries of this subject and it is hoped that future work by other institutions will draw on this thesis to open the subject still wider.

Indeed, apart from 'priming' simulations and for military uses, there will always be room for synthesised terrain models for academic use. Other applications include utilisation as arcade games, in the entertainment industry (films, virtual reality etc.) and for artistic renderings. Synthesised terrain can also be used to test expensive flight simulators while the owners make up their minds which area of real terrain they wish to purchase.

Additionally, until the cost of collecting real DTMs goes down significantly there will always be use for synthesised terrain, if only for testing and simulation purposes. Why buy an expensive DTM when you can synthesise one for a fraction of the price? Organisations such as the Ordnance Survey - charged as they are to make a profit - will always keep the cost relatively high (although the OS now has competitors). One only has to apply for the list of available digital terrain at almost any scale to wonder at the expense - at the time of writing far beyond the resources of individuals for large areas of the

UK (see the *OS Product Price list 1999*). Recent changes at the OS using internet 'e-business' may, however, change this cost model (OS marketing brochures 2001).

Finally, the thesis introduces some radical concepts, albeit in a careful way as this are not necessarily based on the author's training or experience. For example, the concepts of validating synthesised terrain - a paradox some would say - has been tackled. Similarly, specialised algorithms (such as the infrastructure and place name algorithms described in chapter eight) can produce a basis for work in these areas by more appropriately trained researchers.

10.6.3 Opportunities

The opportunities and futures of synthesised terrain are thought to be both tempting and interesting, and the reaction to the article in New Scientist (1997) in the form of letters and e-mails bears this out. The opportunities are grouped into two areas; first, the areas of enhancement that could be applied to this research, represented in part by the software suite Geoforma. Second, the general area of synthesised terrain 'futures' is examined, with some suggestion to those who may 'carry the torch'.

10.7 This research: potential opportunities

The potential opportunities, including areas not covered by this thesis but mentioned as possible future projects, are examined in the following paragraphs.

10.7.1 General Enhancements

As with almost all systems in research and software, the developers can often see another 'stage' or phase whereby improvements and enhancements could be added to the system 'if only we had the time'. This may involve a wide range of activities, from fixing bugs to minor enhancements, right through to major re-writes and new versions of the software. The use of configuration control tools is most useful when dealing with development systems. Geoforma is no different, and had time permitted there are many enhancements that would have been implemented. In the real world, versions of commercially-available software are often released as new versions in order to fix bugs as well as to commit to enhancements or additional functionality. For example, Oracle released Forms 4.5 in 1995 to replace Forms 4.0 (Forms represents Oracle's database GUI development tool) in order to provide some important enhancements (see Appendix A).

The prospective enhancements to the work are divided into two areas; the prospective enhancements to the Geoforma system and the improvements and additions to the theoretical or directional part of the research. The possible advancements to Geoforma are summarised in 10.7.2, whereas the general research enhancements and 'futures' are examined in 10.7.3.

10.7.2 Enhancement to Geoforma

There are several possible enhancements that can be made to the Geoforma suite of software modules. Since these are now no longer easily available to the author it may be redundant to make useful suggestions. However, some general or hypothetical observations are made for completeness.

- **Expansion of AOR to 10^3km x 10^3 km and increase of height post resolution**

This first point emphasises the fact that Geoforma was able to trade off AOR size with resolution, but never to the extent where an area the size of 10^3km x 10^3 km could be used successfully with (say) 100m grid points. Simple mathematics shows that current processing techniques would make such areas (and volumes of data) difficult as a square law applies. However the notion is not impossible to consider processing. The answer to this is a scaling-up of machine resources either to more powerful processors or the use of parallelism to give performance enhancements - indeed parallelism - whether done by multiple program units or multiple CPUs - is a long established technique in IT (Date 1990).

- **General improvement in algorithms for 'better' or more obvious realism.**

This area is clearly a never-ending task - so far a trade-off has been made in order to minimise the time and resources required. In a purely academic situation, the author would have spent far more time polishing the process models and process-response models. One obvious area is to incorporate a template system of river patterns to produce more realistic assemblages of meanders., oxbow lakes, eyots, spilt channels and so-on. This is not really evaluation or parametric methods - it is more a random selection from perhaps hundreds of digitized examples in order to increase realism. Otherwise the creation of - for example - eyots - pleads a 'special case' and a manual edit. Other landforms can be treated in a similar way, so that (for example) tors or inselbergs can be more realistic. This is referred to as 'templating'.

- **Increase in number of land-form types analysed**

Another obvious topic is that one could spend days simply listing the landforms and assemblages of landforms. Indeed Raisz (1962) gave a list of mapping symbols used for landforms and is mentioned to show the range of possibilities for future morphological maps and diagrams. This task is related, of course, to the theoretical side of the research. A tempting area is to be found in glacial and periglacial geomorphology

(Embleton and King 1971). Even as relic forms, outwash features (kames, eskers, moraines etc.) and erosional landforms (Fjords, U-valleys, hanging valleys, roche moutonnees etc.) would be a welcome and interesting addition. The author has also analysed a 1:50,000 sheet from Southern Norway and used Geoforma to create some landforms, although no results have been included in this thesis.

- **Littoral zone representation**

The reason for including this point was because the military sources were interested in amphibious operations: always a high risk undertaking. Synthesised terrain models of beaches could help model quicksand, obstacles, reefs and other features, although of course real operational planning would demand actual maps (Ryan 1960, Blandford 1999). It was felt that a more thorough treatment of coastal simulation and marine synthesised terrain could be carried out as a possible future exercise.

- **Variable resolution representation**

This means that higher resolution 'patches' can be made to appear within a lower or coarser 'background' AOR. This is discussed more fully below under the title 'augmentation'.

- **GIS-aided terrain analysis and auto DEM analysis**

This topic refers to the manual work needed to analyse landforms for physiographic regions prior to applying the parametric methods to obtain a primitive surface. Since this is a manual technique at present, it might be possible to utilise APIs and COTS GIS packages to automate - partly or (more remotely) fully - such activities. Certainly, current GIS packages could be used to obtain parameters such as average slope, maxima and minima (slope angle, relief attributes etc.). The extent to which this can be fully automated is questionable - the 'man-in-the-loop' problem that applies to photogrammetry applies - to some extent - to auto-analysis. However, consideration of the subject is certainly worth more effort as perhaps a 50% or 60% increase in efficiency could be obtained.

One restraining factor is that humans have a distressing tendency to believe what computers tell them - manually analyzing a map AOR at least has the advantages that it can be checked by other humans, and it familiarises the users with the area often to their advantage. The author has personally found this latter point to be most valuable; a gradual familiarity with a map gives an interesting and stimulating expectation about the actual terrain; photographs and (if possible) field visits often bear out initial views, or they can (in some cases) completely baffle the operator with an expectation gap. Whatever the outcome, keeping the 'man in the loop' had advantages in helping to understand the terrain. If senior officers in the First World War tore themselves away from their maps and visited the front line one might suppose that catastrophic tactical situations - such as the battle of Ypres - might not have been such a tragedy (Smithers 1986).

- **Improved visualisation and 'real time fly-bys' over 3D terrain**

Clearly there is always room for the interactive part of any software to be improved. Improvements can take many forms, divided here into general and Geoforma suite specific:

- **General**

    - Better, clearer and less cluttered layout

    - More screens to reduce clutter but improve functionality

    - Help facility (context related if possible)

- Facility to change screen *properties (colours etc.) if not* already provided as part of GUI package

- Web front end to allow system to be run over the internet

- **Specific**

    - Better visualisation of component landscapes

    - More sophisticated manual edit facility

    - Facility to advise user of 'non-viable' boundaries

    - Better advice and layout of landscape development

    - Better performance, allowing higher resolution, with dynamic, run-time implementation

    - Ability to save a promising landscape at a certain stage, but then backtrack to that stage if subsequent activities are unsuccessful (known in IT as 'rollback and recovery')

    - Link to other facilities, such as on-line geomorphological help, whereby a brief geomorphological summary can be presented in a window (as is done in Microsoft Windows Help facilities) for the layman

    - 'Thinner' client software (enabling smaller PCs to be used to run the software.

Finally, some self-explanatory enhancements are suggested as follows:

- Better GUI presentation logic and error checking

- More iteration (with error checking and 'rollback' choices) for the human geography/infrastructure routines

* Higher component of automatic parametric analysis, so that the user can enter a region's physiographic parameters more easily and far more rapidly.

* Augmentation

Augmentation is a term applied originally by certain MOD users to the possible future adaptation and usage of the algorithms - in a general sense - to produce additional features. In essence, augmentation would have given the military training user the power to add in areas of specific interest - such as a patch of high resolution data representing an ambush site or an area of urban settlement to simulate 'house-to-house' fighting. The term was then utilised as a general descriptor for any 'add-on' feature - whether in the military field or not. To summarise, augmentation:

* Adds value to real terrain data

* Provides high resolution data not normally found for available 'real terrain' data sets

* Provides route to dynamic generation of high resolution terrain patches during simulator run-time

Away from the military scenarios, Augmentation would also allow a geomorphologist to create areas of interest against a lower resolution background. This could be most useful, as the standard Geoforma software treats the AOR as a single resolution; if too coarse then individual features could be overlooked; whereas if it is too fine then the data volume would be too much for even modern servers to process in anything like real-time. One solution would be to have a high resolution patch in a lower resolution background - DLMS DTED does just this, whereby high resolution DEMs are available as (usually highly classified) patches within the overall DLMS structure. This demonstrates that certain landforms become 'visible' only at the higher resolution in the AOR.

Other augmentation concepts include adding in some real terrain data to a synthesised terrain background to achieve some goal. For example, the synthesised terrain could be used to produce distant views in a high resolution 3D simulation (like an arcade game), where the foreground is based on a real map (streets and buildings) but the glimpses of the landscape in the distance are irrelevant so they can be synthesised (but not ignored). Although this may sound an odd application, several military training experts have stressed to the author the importance of having a quasi-real 'horizon' as opposed to an absurdly unrealistic fractal landscape or a flat plain. Finally, increased feature density is another augmentation technique, where - for example - double the number of houses could be represented in one or more patches laid out across the AOR.

10.7.3 General Enhancements

Away from the possible enhancements and augmentation involving military users and the Geoforma software, there are many topics which the author would have liked to pursue in greater detail, or simply to have included at all. These mostly involve an examination of the literature and synthesis issues associated with different geomorphological environments and landforms, at different scales and different areas of the world. This, of course, is too complex and generalised in itself to be an aim, so it can be condensed into certain categories of interest to the author:

- Selection of an area in the UK (such as South West England in its entirety) and a thorough synthesised treatment of the geomorphological and human geography/infrastructure.

- Better treatment of the modelling of coastlines, perhaps again based either on some 'generic' landforms or on one or more physiological regions.

- Auto-validation techniques (not necessarily linked to Geoforma)

- Better modelling of human geography and the man-made environment. This is beyond the author's training and inclination, so it would be a good research topic for others.

- Planetary synthesised terrain - should raw data become available at the appropriate resolution and scale for Mars or other planets with a solid surface (i.e. not gas giants). This could help simulate landing procedures if - for example - a manned Lunar or Mars mission went ahead and the real data resolution or existing DEMs precluded accurate simulations. This is not so far fetched as it may seem - some simulation work has already been done with respect to Mars (Kelley and Malin 1987) and the subject may increase in popularity as planetary research vehicles carry out 'fly-bys'.

10.8 Cost advantage

The cost advantage of producing 'made to order' geomorphologically-viable synthesised terrain has been stressed several times in this thesis, and although this was the reason for the MOD undertaking several synthesised terrain projects it must be stressed that the author is personally more concerned with the subject as an academic or research tool. Clearly there is an initial investment in the people, tools and research that combine to make practical software suites such as Geoforma, but depending on the requirements this was found to be vastly cost-effective when compared with the high prices of 'real world' DTMs.

This cost advantage is expected to last for some years to come, although a factor that may work against the 'cost argument' for synthesised terrain approach in the coming years is the proliferation of remote sensing platforms and the increasingly automated use of technologies such as Lidar. Already this is having an effect, and where once firms undertook to survey land by aircraft or satellite followed by extensive photogrammetric techniques and map-building, Lidar can pave the way for easier - and therefore cheaper - surveys. How this will affect the cost is not known as yet, but it is an area worth watching.

10.9 In Summary

Perhaps one of the most satisfying parts of the synthesised terrain work is when people 'recognise' a synthesised area as part of a region. This was particularly so in the early, somewhat unscientific validation exercises based on the figures in chapters 5, 6 and 8). Perhaps the author becomes over-accustomed, even complacent, about what can be done by a composite approach using powerful methods and GIS tools. It is healthy to be reminded that not all maps were successful (some of the early attempts were almost amusingly inept). However, the principles and the sheer overlapping depth of subjects that yield such results give output that cannot be less than satisfying to the author, and to those who have been connected with the work.

For now, synthesised terrain is still a useful - and fascinating - way of exploiting geo-spatial knowledge and techniques to achieve real academic and practical goals. Although never claimed to be a panacea, the synthesised terrain methods reported in this thesis served a practical purpose and exercised geomorphological models in a helpful and interesting way. The research, algorithms and software packages are thought to have proved their worth. It may now be for others to enlarge the potential scope of this legacy 'bequeathed' by the synthesised terrain research presented in this thesis.

Perhaps the last word belongs to Kennie and McLaren (1988). These workers were personally aware of the author's struggle towards realism and gave words of encouragement, and at the end of a paper in which they discussed DTMs and landscape visualisation, they remarked (of their own work):

Despite realism being a distant target, it acts as a convenient measure of our techniques and understanding and will continue to be relentlessly pursued to our continuing benefit.

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APPENDIX A: SOURCES OF RELEVANCE TO THE THESIS

A-1 MOD

The permission to use some of the MOD information has been taken from selected DERA contract minutes *ref.: NNR/25b/FY95/96* and the copyright referring to certain selected diagrams. The author is also grateful to RED Scientific, Alton, for help in chasing up some elusive information. Geoforma, or its derivatives, are available through the appropriate authorities (Land Simulations Group) at MOD or through RED Scientific.

A-2 Oracle

The author is also grateful to the Oracle Corporation (UK) Ltd for providing some information not normally available to the public. With regard to Forms development, behind the scenes, some 800 bugs or 'features' were also dealt with while the product was at version 4.5 (source: *Oracle Forms Documentation 1996, Copyright Oracle Corporation (UK) Limited: Internal distribution*). The product is now at version 6.0 and appears to be working extremely well.

APPENDIX B: IT CONSIDERATIONS

B-1 IT considerations

IT specialists and terrain modellers have long been aware that there is an inevitable 'trade-off' in IT between resolution and disk storage or volume, and consequently CPU performance. Yet the more points - the greater possibility of accuracy. The effects of resolution and accuracy (and the possible trade-offs) are especially important for remote sensing, for example.

Consider a matrix (e.g. a PC screen or a file of height datum points), where a 50 X 50 grid would yield 2500 points. At, say, one byte per datum point, this is a mere 2.5 Kbytes, or 2500 ASCII characters (as ASCII characters are always stored in 8 bits, where by definition 8 bits = 1 byte or 'by eight'). Doubling the number of grid points along the X and Y (horizontal) axes to 100 x 100 datum points gives us 10000 points (10 Kbytes) to store and process, whereas repeating the process to yield 1000 x 1000 points gives a number close to 1 MegaBytes (actually 1,240,000 bytes). The effect of 'doubling' resolution therefore squares the number of datum points, and in turn such significant data volumes can lead to a noticeable drop in CPU performance, yet more detailed information can be processed. The choice is really dependent on the desired conclusion, although until recently there were hardware limitations on such matters. For example, in the late 1980s and early 1990s, when typical disk volumes were rarely more than tens of MegaBytes, this was a significant point, although it is perhaps less so today when a typical PC rarely boasts less than 1 GigaBytes (actually 1024 MegaBytes) of available disk storage or volume - a significant leap from the 2Kbytes disks of 1980. Moreover, computers today are estimated to work 600 times faster than in the early 1980s (Comer 2000) so the processing is orders of magnitude faster. However, since IT resources are normally used to capacity, this merely shifts the problem so that larger (or more detailed) data sets can be processed.

B-2 3GLs and 4GLs

A 3GL is defined in this way - it is a powerful language that can be difficult to learn but invokes processes at a low level (that is, it is not 'transparent' to the user in the way that a 4GL - or Fourth Generation Language - operates). This had good points and bad points. The good points included a high level of control at the 'bits and bytes' level of the computer, whereas 3GLs had the disadvantage of requiring skilled programmers who might be working in relatively resource-starved software development environments. Incidentally - 4GLs are normally associated with database languages such as SQL. They are no better or worse than

3GLs - they are just functionally different and are closer to 'understandable English' (Date 1994). In the late 1980s and early 1990s one might use a 3GL for real-time or mathematical computation work and a 4GL to access RDBMS information in the same program. Software has moved on somewhat from the mid 1990s so that 'modules' or programs tend to be written in 'protective' development environments, where syntax, module linking and debugging (testing) can be carried out using a GUI form or even web-based visual aids.

APPENDIX C: TOR ALGORITHM (POSITIONAL DATA)

C-1 Tor Algorithm (Abbreviated version)

The algorithm to make tors was based on the work of Linton (1955), Palmer and Nielson (1962) and others described in the test, as well as on the author's own field work and observations. The algorithm assumes a DEM in either file matrix form (where only the height - z) is recorded and the (x, y) positions are inferred from their position in the file matrix) or DTED format.

The algorithm is written as a Plain Language Algorithm (PLA) as follow:

- Sweep DEM, noting attribute file for summits and joint spacing characteristics.
- Using GUI set-up, view the landscape in 3D and assign (a) number of desired tors (b) whether valley side, summit (or if coastal) cliff-top tors are required.
- Ensure that a prepared 'tor attribute' file (filename = *tor_attribute_grnt)* is available. This assigns the maximum dimension of the tors as early attempts produced tors of unlikely heights and shape.
- Run sub-module *tor_maker_3.7*
- This routine scans through the AOR and selects cells or positions marked by an (x,y) position (or a grid co-ordinate or Lat./Long. If desired).
- Enter test/iteration loop for tor conditions: this tests correct relief attributes (e.g. summit), joint spacing should reflect relatively massive rock (if data available), and on a random basis chooses one of several tor types from the matrix:

Size	Shape	Associated Features	Colour	Other
Large	Rhomboidal	Vertical Faces	Brown	Overhang
Medium	Massive	Horizontal Faces	Grey	Obscures other feature?
Small	Fragmented	Rock Field	Composite	N/A

Appendix Table C.1 Matrix for tor algorithm

The matrix can take one attribute from each column. Thus a Large tor can be Massive (few joints visible), grey and can have overhanging features. The attributes in the first 4 columns are mutually exclusive.

When the program runs the tors (using predefined symbols) are overlaid on the 3D landscape of the AOR as a check. The program is largely trial and error but some good results have been produced. What it does not do is take account of 'special cases' such as a tor complex or a collapsed tor system. However the algorithm was written to be generic.

The alternative to the 'scan' process is simply to define, in (x,y) positions, where the tors will be built by manually indicating this on the screen. The advantage of using the semi-random routine is that the tors were felt to be 'more realistic' in the author's mind (the example in chapter six was one of the best 'random' exercises completed).

APPENDIX D: WEB SITES

This appendix reports on some web sites which have been found by searches or by personal correspondence. Web sites are 'places' on the WWW (World Wide Web) or the internet - where virtually anyone with the resources can publish material on virtually any topic (Gralla 1999). However they are prone to disappear and therefore have an ephemeral nature. For this reason a small sample was obtained to demonstrate the synthesised terrain visible by means of the web. The ability to access such material is governed by the IT resources of the 'viewer' (using a 'browser') - one most have a PC or client machine with access to the internet (or intranet as the more internal, private systems of networks is known). The WWW is maintained by hundreds of thousands of 'servers' around the world.

The problem with web sites is that they can change or even disappear. Unlike published papers and books - which may go out of print but are almost always retrievable from a library - web sites may be 'taken off the air' - sometimes never to return. At least two promising synthesised terrain web sites have met this fate before the author could print out material. As far as synthesised terrain is concerned therefore, some examples are extant in spring to late summer 2000 and are listed below for general information only - this is not intended as an exhaustive list nor can the permanence of any particular URL be guaranteed. Some real-terrain examples are also given by way of comparison.

- **http://wien.ac.at/studentwork/CESCG97/marak/node3.html**

This site ('owned' by Ivo Marák) looks at synthesised terrain surfaces from a point of view of mathematical modelling. Most of the references are to computer graphics or mathematical papers. However, using random midpoint displacement (fractals) some 'realistic' surfaces are shown - although no geomorphologically-viability is suggested.

- **http://wien.ac.at/studentwork/CESCG97/marak/node6.html**

This is a similar site from the same source, dealing with the creation of mountains and rivers. An illustration using fractals - (random midpoint displacement methods) is given in Figure 2.5.

- **http://www.metavr.com/97F-SIW-107.html**

This web site is dedicated to the Rapid Terrain Visualisation (RTV) programme that is designed to provide Digital Terrain Data (DTD) to military units for intelligence and analysis, mission planning, and course of action analysis. This enhances real terrain but it is not clear from the web site how much 'synthetic' terrain is involved. The RTV Transform Team is tasked with providing software tools to teams in the field, as well as runtime data sets for low-cost visualisation applications. Interestingly, the system uses what it calls 'building the Synthetic Natural Environment (SNE)'. This process starts with a complete triangulation of the terrain surface, then 'georeferenced data' are converted to the Global Co-ordinate System (GCS) to preserve the geometry of the source data. All SNE data added to this framework are available in a 3D interactive modelling application called the Geospatial Workstation (GW). There is no geomorphological validation: the system is designed to help military planners with GIS and 'visualisation' systems. Apparently related to this site is the following site, where good quality simulated 3D pictures can be found and are available on a commercial basis (again with no apparent geomorphological validation):

- **http://www.metavr.com/reFrameIndex.html?http://www.metavr.com/mout-complete.html**

This web site allows the user to access several options and view a number of good quality military-based synthesised terrain views and simulation products.

- **http://www.mors.org/67morss/wg29.html**

Searching for 'Natick' on the web produces some interesting results. The US Army are still carrying out Terrain-related work, and there are several web sites related to synthetic terrain, some of which refer to the SNE system (see previous website). Simulations will be required to interoperate with each other and with Command, Control and Communication systems in the Digital Capstone Exercise and subsequent training exercises. At STRICOM, the Warfighter Simulation/Joint Simulation System (WARSIM/JSIMS) Synthetic Natural Environment (SNE) team is working closely with the Synthetic Theatre of War (STOW) programme to provide a single, seamlessly integrated representation of the land, sea, air, and space, designed for reuse in other simulations and with consideration to interoperability with other systems. Related efforts supporting the goals of reuse include: DARPA's Advanced Simulation Technology Thrust (ASTT), JSIMS Terrain Generation Process, and Synthetic Environment Data Representation and Interchange Specification (SEDRIS). However, none of the papers or websites gave any indication of validation or geomorphologically-viable terrain, except to point out that the terrain simulations were 'realistic'.

- **http://www.computer.org/conferences/ais94/marty/paper.html**

This web site, from the US military, discusses synthesising terrain for route planning. Route planning is another area that is frequently associated with automatically guided vehicles (AGVs) and it has been mentioned briefly in the work done on the UMV project (Griffin

1986). Some work has been done in this area but it tends to be related to an industrial project (see for example Huss and Weber 1983), which addresses the effects of terrain and path resolution on generated path quality and compares the results of automated planning to human generated plans. This web site looks at computer route planning providing the backbone for automating simulated behaviour of man and machines on synthetic terrain.

The approach exploits techniques borrowed from Geographical Information Systems technology. Routes are tailored to meet various requirements. The authors (Marti, J. and Bunn, C. - the full paper is on the web site) have experimented with several characteristics such as exploiting available ground cover to hide (dead ground), and avoiding or using terrain features such as roads, rivers, and fords. However the experiments covered by this work exploit only minimal elevation change and there is no geomorphological input. One interesting point is that the authors contend that conventional wisdom states that automated route planning requires very high resolution terrain data, whereas the experiments described begin to quantify the relations between resolution, representation, and human generated plans. Route planning is felt to be an important component of both computer simulations and real world planning (by the authors). In their words:

> *Combat simulations exploit route planning to automate some of the drudge work normally associated with laying down many highly detailed plans or provide automatic reactivity to changed situations. This technology is also applicable to wild fire simulations, disaster response planning, herd and swarm simulation, wilderness road planning and the like*

- **http://www.oslo.sintef.no/wavelets**

This site, based on the University of Oslo in Norway, is concerned with using Wavelets to create surfaces. It is a good source for the theory and application of Wavelets (which are considered in chapter three) and there are many colourful 'surfaces', but again, although 'realism' is discussed in the web site for flight simulators, no geomorphological viability is apparent. Written references on wavelets related to this site have been produced by Floater and Quak (1998, 1999).

There are other sites, and any new or interesting examples as the thesis goes to 'press' will be mentioned in an appendix (given the ephemeral nature of such media).

- **http://www.multimania.com/bianco/**

This web site (in Italian), has been created by Luc Bianco, claims to make a system called Terragan, which produces realistic-looking terrain with a 'photographic' bias (in other words some real-world light and texture effects are included, such as the relative strength and position of the sun for terrain shadow effects). The text does not reference any geomorphological validation of the results, which are created using fractals and a number of PC-based GUI (windows).

- **http://www.ericjorgensen.com/html/tm.htm (Terrain Maker)**

One may download a product called Terrain Maker from the web site **http://www.ericjorgensen.com/html/tm.htm**. This is a crudely-coloured but relatively effective synthesised terrain system, downloadable as a software package which uses POVRAY (a 3D perspective tool discussed elsewhere in this thesis) for display purposes, and claimed to be a 'landscape editor'. Although there are no apparent geomorphological qualifications, the author of Terrain Maker claims that 'natural looking' terrain can be synthesised. Indeed, 3D views with different heights and colours can be created quite easily using a simple GUI. Terrain Maker is interesting in that 'sea level' can be altered so that the 3D view can be of a simulated inland region, it can have a coastline of sorts, or it can be an archipelago. The resultant terrain is not very realistic by almost any standard, however. Finally this web site is useful in that it gives an URL list of similar sites (including the Terragan site), although at the time of writing many of the URLs did not produce anything except errors.

- **http://www.gamedev.net/reference/programming/features/noiseterrain/**

This web site is typical of many such sites that use 'improved' fractals and other well-known methods for arcade game synthesised terrain. The methods are used both for the games and for generating and rendering terrain. The terrain is claimed to be 'usable and realistic' (but not geomorphological-viable).

- **http://hpux.dsi.unimi.it/imaging/DTM.html**

This is a web site in involved with the 'Visualization of Digital Terrain Models'. To quote the web page: 'The research has been developed as a collaboration with the CNR institute IRRS (Research Institute on Seismic Risk), Remote Sensing Department, co-ordinated by Dr. Alessandro Brivio. A digital terrain model can be reconstructed by interpolation of data from iso-elevation lines, or from a regular grid of elevation data reconstructed adopting stereo-images taken from aero or satellite survey. The interpolation is based on linear and Kriging techniques; a fractal interpolation technique is also available. The interpolated DEM is the basis for the photorealistic visualisation method. TISS (Territorial Image Synthesis System) is an interactive program that supports a geologist to reconstruct and explore a DTM. The exploration is based on Virtual Reality methods, in particular walk through: also an animated virtual fly can be created interactively. Future versions of the system will include utilities to explore the DTM, e.g. man made elements for environmental impact evaluation, cut and fill computation, erosion models, flood simulation, iso-elevation lines display etc.'

- **http://graphics.stanford.EDU/~liyiwei/project/texture/**

This project from Stanford in the USA concentrates on texture in synthesised terrain. The web site states that "Texture is a ubiquitous visual experience. It can describe a wide variety of surface characteristics such as terrain, plants, minerals, fur and skin. Since reproducing the visual realism of the real world is a major goal for computer graphics, textures are commonly employed when rendering synthetic images. These textures can be obtained from a variety of sources such as hand-drawn pictures or scanned photographs". A reference paper is given as produced by Li-Yi Wei and Levoy (2000).

For comparative purposes there are the following web sites:

- **http://www.ordsvy.gov.uk/**

This is to show a contrasting viewpoint to synthesised terrain - this is the UK Ordnance Survey's website. It does not deal with synthesised terrain at all, but it gives the visitor to the site some idea of the range and high cost of products.

- **http://graphics.lcs.mit.edu/~seth/pubs/taskforce/paragraph3_3_0_0_2.html**

Thomson Training and Simulation (a subsidiary of Thomson) has developed a new generation of machines for image synthesis. The approach followed departs from its predecessors in that instead of relying on massive, dedicated hardware, the new machines are mostly software-driven and use standard processors (for example, the i860). This change allowed the flexibility to provide new functionality, such as inserting moving objects or supporting different types of animation. A new *polygon engine* was built to allow the user to view collections of thousands of non-convex polygons with holes at interactive rates. In addition, a fully dynamic algorithm for constructing Delaunay triangulations was developed, which runs in real-time on the new machine. Many of the underlying ideas were borrowed from the recent work on randomised algorithms in computational geometry. In particular, the algorithm uses a hierarchical representation, the so-called Delaunay tree based on the work of Buttenfield and McMaster (1991), Boissonnat and Geiger (1993), Boissonnat and Teillaud (1993), Asano and Kimura

(1995) and Bouma *et al* (1995), with contributions from Brost and Goldberg (1996). This resulted in a project to construct a terrain in real-time and automatically to adapt the database to the specifications of the graphics device as well as to the distance of the observer from the terrain.

- **http://www.nlh.no/ikf/gis/dcw/**

The Digital Chart of the World (DCW) is the world's most comprehensive 'public domain' GIS database with a nominal scale of 1:1000,000. The major data quality aspects examined were positional line accuracy and completeness. The project was carried out by staff and students from the Dept. of Mapping Sciences, Agricultural University of Norway, and staff from UNEP/GRID - Arendal, one of the nodes in the UNEP/GRID network of co-operating environmental data and information centres. The objectives of the DCW project are stated as:

- To theoretically examine *(sic)* some data quality characteristics (positional line accuracy and completeness) of spatial databases.
- To review and summarise present use and quality experiences from DCW users world-wide by means of an Internet based survey.
- To provide an extensive completeness report of the DCW database using existing material on the DCW and its source map series, the Operational Navigation Charts (ONCs).

The beneficiaries of the project are intended to be:

- The GIS community, both data producers and users, both practitioners and academicians, concerned with quality aspects of geo-referenced data.
- In particular, all users of DCW data including UNEP/GRID in general and in particular the GRID centres and co-operating centres using DCW data in various projects.

- **http://www.3dillc.com/rem-lidar.html**

and

- **http://www.lasermaps.com/**

are both web sites typical of the detailed DEM and general terrain mapping that can be carried out by the Lidar or LIDAR (Light Detection and Ranging) system. An internet search on the term 'Lidar' will reveal many returns, although most are involved with atmospheric research and not all are terrain mapping. However Lidar techniques are becoming more important and may eventually affect the price of DTMs and DEMs so that the price advantage of synthesised terrain is offset or even nullified. However this is probably some way off in the future, as Lidar technology still requires an aircraft or space vehicle platform.

To summarise; Web sites are ephemeral and do not have the same 'quality control' or vetting procedures that ensures the good standard of papers in learned journals or scientific text books. This is demonstrated by attempting to access some of the URLs recommended by the Terrain Maker site (see above) - about half of which give errors or simply do not exist at the time of writing (Summer 2000). Nevertheless, the WWW does give useful information when they have reasonable permanence or if the author (such as Marák) can be traced to related articles or publications.