DEVELOPMENTS IN SOIL SCIENCE • VOLUME 33



# **GEOMORPHOMETRY** Concepts, Software, Applications

EDITED BY Tomislav Hengl & Hannes I. Reuter



# GEOMORPHOMETRY

Concepts, Software, Applications

# Developments in Soil Science

SERIES EDITORS: A.E. Hartemink and A.B. McBratney

#### On the Cover

The figure on the cover shows an unsupervised classification of topography from SRTM30 DEM data by an iterative nested-means algorithm and a three part geometric signature (Iwahashi and Pike, 2007 — available at http://gisstar.gsi.go.jp)

# GEOMORPHOMETRY

# Concepts, Software, Applications

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This book is dedicated to all geographers and earth scientists, from which two must be singled out for special mention: Waldo R. Tobler — methodological revolutionary, conceptualiser of Analytical Cartography, and hero to numberless quantitative geographers; and Peter A. Burrough — one of the founders of geoinformation science and mentor to a generation of GIS scientists.

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### FOREWORD

#### WHY GEOMORPHOMETRY?



We began to think about a geomorphometry book in the summer of 2005 following a request to suggest auxiliary data that would assist the automated mapping of soils. The first thing that came to mind, of course, was — Digital Elevation Models (DEMs). The longer we considered our response to the request, the more we realised that a substantial gap had opened between the formal discipline of land-surface quantification and a vast informal, and rapidly growing, community of DEM users.

The practical aspects of morphometric analysis seemed to us neglected in the literature. Apart from Wilson and Gallant's "Terrain Analysis: Principles and Applications" and Li, Zhu and Gold's "Digital Terrain Modeling: Principles and Methodology", few textbooks are suited both for training and for guiding an inexperienced DEM user through the various steps, from obtaining a DEM to carrying out analyses in packaged software. It was our experience that, although irreplaceable, Wilson and Gallant's book is not ideal for either purpose; not only it is primarily a compilation of research or review papers, but it relies heavily on Ian Moore's TAPES software, a comprehensive package to be sure but just one of many now available. Meanwhile, new parameters and algorithms for processing DEMs were circulating in the scientific literature; an update and summary of the field seemed increasingly appealing. Richard Pike later told us that he (and others) had pondered a geomorphometry text for many years. We also discovered that there is quite some disorder in the field. A major problem is the absence of standards for extracting descriptive measures ("parameters") and surface features ("objects") from DEMs. Many users are confused by the fact that values of even basic parameters such as *slope* gradient may vary — depending on the mathematical model by which they are calculated, size of the search window, the grid resolution... although the measures themselves might appear quite stable. Serious issues also exist over operational principles, for example, pre- and postprocessing of DEMs: should unwanted depressions (sinks, or pits) be filtered out, or not? which algorithms should be used to propagate DEM error through subsequent analyses? should DEMs be smoothed prior to their morphometric application or not, and if so, by how much? These and other questions got us thinking about many aspects of land-surface quantification.

In November 2005, we prepared the initial draft of a Table of Contents and immediately agreed on three things: the book should be (1) practical, (2) comprehensive, and (3) a fully integrated volume rather than an *ad hoc* compilation of



FIGURE 1 Participants in the first meeting of the authors, Plasencia, Spain, 18–22 May 2006.

papers. We also knew that our goals would be more likely achieved in collaboration with a number of co-authors. Initially, we invited ten colleagues to join us but the number slowly grew, along with interest in the book. Our third objective posed difficulties — how to synchronise the output of well over a dozen authors? To solve this problem, we launched an online editorial system that allowed us to exchange documents and data sets with all the authors, thereby encouraging transparent discussion among everyone in the group. It became clear that there would be many iterations before the chapters were finalised and authors sent in their last word.

Our action leader at JRC, Luca Montanarella, soon recognised the importance of this project and supported us in organising the first authors' meeting, which was kindly hosted by Victor Olaya and Juan Carlos Gimenez of the Universidad de Extremadura in Plasencia, Spain. At this meeting, we found ourselves convinced of the effectiveness of a group approach to the writing; enthusiasm for the book was overwhelming. In response to last-minute invitations, Paul Gessler and Ian Evans joined the group (Paul took less than 24 hours to decide to make the 12,000 kilometre trip from the western U.S., even though the meeting would convene in just 4 days) and immediately provided useful feedback.

It was Ian Evans who *rocked the boat* by opening a discussion on some of the field's terminology. First to be scrutinised, and heavily criticised, was "*terrain*". Gradually we began to see the problems arising from its use and elected to adopt less ambiguous language. We understand that whatever our arguments, the wider user community will not readily abandon *terrain* and *terrain analysis* in favour of our preferred *land surface* and *geomorphometry* (indeed, there is not 100% agreement among this book's authors), but we hope that the reader will at least agree to think along with us. The Plasencia meeting further revealed that most authors were in



**FIGURE 2** Geomorphometrists are easily recognised by their obsession with shape — explaining a morphometric algorithm often requires much use of the hands.

favour of pricing the book at a non-commercial rate, thereby opening it up to the widest possible readership — yet without jeopardising its scientific and technical content.

The meeting also led us to suspect a "gender gap" in the field. Despite their many contributions over the years, women geomorphometrists were absent at Plasencia. We hasten to add that we invited several women colleagues to join us, but only four were able to participate in preparing this first edition. We look forward to an improved balance in the next, and succeeding, editions of this book and take encouragement from Peter Shary, who reported from the 2006 Nanjing Symposium on Terrain Analysis and Digital Terrain Modelling that the number of younger women now working with DEMs (at least in Asia) is clearly on the rise.

During final editing of the book's initial draft we decided to prepare a stateof-the-art gallery of land-surface parameters and objects, to assist less experienced readers in applying DEMs to their best advantage, and then to support an independent Web site to encourage further evolution of the Geomorphometry Project. You are now invited to visit this site, post comments on it, evaluate software scripts and packages, upload announcements of events or jobs, and eventually post your own articles. The floor is open to all.

#### WHAT CAN YOU FIND IN THIS BOOK?

The volume is organised in three sections: theoretical (concepts), technical (software), and discipline-specific (applications). Most of the latter are in the environmental and Earth sciences, so that the book might best be compared with that of Wilson and Gallant (2000). Our book differs, however, in that it offers technical details on a variety of software packages and more instruction on how to carry out similar data analyses yourself.

This book is more about the surface properties that can be extracted from a DEM than about creating the DEM itself. To appreciate our chosen operational focus, a basic acquaintance with geographical information systems (GIS) (Burrough, 1986) and (geo)statistics (Goovaerts, 1997) will be helpful. Readers who require added technical information on DEMs and how to generate them should consult the books by Li et al. (2005) "*Digital Terrain Modeling: Principles and Methodology*" and Maune (2001) "*Digital Elevation Model Technologies and Applications: The DEM Users Manual*".

Each of the book's three sections consists of nine or ten chapters that follow a logical sequence from data processing to extraction of land-surface parameters and objects from DEMs. Many chapters overlap in both content and examples, illustrating not only the many *types* of land-surface parameters, but also their *variants* — differing parameter values calculated from an identical DEM by different software. Links to external sources and important literature can be found at the end of each chapter, and well over 100 text boxes flag (important) *remarks* throughout the book. All major types of land-surface parameters and objects, together with a quick reference to their significance and interpretation, are listed in the gallery of parameters and objects available on the Geomorphometry Web Site. A list of references and an index are provided at the end of the book.

#### Part I: Concepts

The book's opening Chapter 1 will first orient you to the field of geomorphometry, its basic concepts and principles, and major applications. This introduction is followed by a historical review of the discipline, from before the first contour lines to the computer programs by which early DEMs were processed. You will also find a detailed description of the Baranja Hill case study, which is used to demonstrate algorithms and applications throughout the book.

Chapter 2 in Part I is a mathematical introduction to modelling the land surface. Following a discussion of the most important model properties, including surface-specificity, is a list of mathematical models and data structures to represent topography and its intrinsic attributes, such as scale dependence, multi-fractality, and the fit of a model to the true land surface. Special attention is accorded formulas for calculating first- and second-order surface derivatives.

The most common sources of digital elevation data are reviewed in Chapter 3. Each DEM source is described in terms of the equipment or hardware used to collect elevation data, as well as the advantages and disadvantages of postprocessing in converting the raw data into a DEM. Also compared are such key characteristics of the different sources as cost per km<sup>2</sup>, typical footprints, postprocessing requirements, and data accuracy and precision.

Chapter 4 is devoted to techniques for improving the quality of DEMs prior to geomorphometric analysis. Included are algorithms to: detect artefacts, systematic errors, and noise in DEMs; deal with missing values (voids), water bodies, and tree-canopy distortion (e.g. in SRTM data); and filter out spurious DEM depressions. The chapter closes with a discussion of simulation techniques to minimise DEM error.

A geostatistical technique to model uncertainty in DEMs and analyse its impact on the calculation of land-surface parameters (slope, wetness index, soil redistribution) is introduced in Chapter 5. The focus is on propagation of DEM error through subsequent analyses using the sequential Gaussian simulation.

Chapter 6 is an overview of *"basic"* morphometric parameters, measures derived directly from DEMs without added special input. The measures range from local land-surface parameters (slope, aspect, solar aspect, curvature) to regional parameters (catchment area, slope length, relative relief) and statistical parameters such as terrain roughness, complexity, and anisotropy. Each measure is illustrated by the Baranja Hill test site.

Following in Chapter 7 are hydrological land-surface parameters for quantifying water flow and allied surface processes. This overview will guide you through the key concepts behind DEM-based flow modelling, again, illustrated by our Baranja Hill case study. Methods for parameterising the physics involved in moving mass (water, sediment, ice) over an irregular surface (topography) are explained, as well as related parameters and objects derived from modelled flow.

Chapter 8 contains an extensive review of solar radiation models and approaches to quantifying exposure of the land surface to climatic influences. First discussed are algorithms by which incoming solar radiation may be estimated from DEMs. Topo-climatic modelling is then extended to the estimation of land-surface temperature, precipitation, snow-cover, and exposure to wind and the flow of cold air.

The final Chapter 9 in Part I introduces landform types and elements and their relation to continuous topography *versus* specific geomorphic features. Next described are techniques for extracting landform classes, either from a list of predefined geomorphic types or by automated extraction of generic surface facets from DEMs. An extensive comparison of approaches to landform classification highlights the value of geomorphometric standards and data-systems that could win wide (international) acceptance.

#### Part II: Software

Chapter 10 opens the middle third of the book with a general inventory and prospect of all packaged computer programs suited to geomorphometry (of which we are aware), including software not demonstrated in this book. The remaining chapters illustrate eight well-known packages currently available for land-surface analysis, ranging from commercial (ArcGIS) to medium-cost (RiverTools) and freely-available (including open-source) (SAGA, GRASS, ILWIS, LandSerf, TAS, MicroDEM) software. Five chapters are authored by the originators of the software, and three by later developers or expert users; each chapter follows a common structure:

- Description of the software, its origins and target users, and how to acquire the package and install it.
- Using the software package for the first time what it can, or cannot do; where and how to get support.
- How to import and display DEMs, using our Baranja Hill case study.
- Which land-surface parameters and object-parameters can be derived from the package, and how they are calculated.

- How particular land-surface parameters and objects can be interpreted and applied.
- Summary of strong and weak points of the software, any known bugs, and how the package may be expected to evolve.

We intend that each chapter serve a dual purpose, as a user manual and as a review of scientific information. For readers requiring further support, links to original user guides, mailing lists, and technical documentation and where to download them are given in each chapter.

#### Part III: Applications

The final section of the book exemplifies the role of geomorphometry in geo- and environmental sciences ranging from soil and vegetation mapping, hydrological and climatic modelling, to geomorphology and precision agriculture. Chapter 19 introduces the role of digital land-surface analysis in creating maps and models across a broad spectrum of disciplines. It explains why DEM analysis has become so essential for quantifying and understanding the natural landscape. The chapter reviews basic concepts underlying the many uses of geomorphometry as well as how these applications incorporate automated mapping and modelling. It also describes some of the mathematical, statistical, and empirical methods by which predictive scenarios have been modelled using land-surface data.

Subsequent chapters of Part III describe specific cases of automated DEM analysis in various disciplines. These examples are not necessarily all-encompassing, but illustrate some of the many different approaches to using geomorphometry to generate and interpret spatial information. Each of the next eight chapters follows a common structure:

- Introduction to state-of-the-art applications, explaining the importance of geomorphometry in this field and reviewing recent research.
- Guided analysis of an example, usually the Baranja Hill case study, including an interpretation of the results.
- Summary of opportunities and limitations as well as suggestions for future research.

In considering the prospect for geomorphometry, the book's closing chapter *peers into a crystal ball* — what breakthroughs might emerge from future advances in technology? Which concepts, applications, and societal needs are likely to drive the discipline? How dramatic an increase in detail and accuracy can be expected of future DEMs? The chapter also includes a proposal for the design and operation of a geomorphometric atlas of the world that could provide a reference data-repository for most applications of DEM-derived information.

#### **CLOSING THOUGHTS AND ACKNOWLEDGEMENTS**

This book is intended primarily for (a) universities and research institutes where graduate or post-graduate courses are conducted in geography and other envi-

ronmental and geo-sciences, and (b) GIS specialists and project teams involved in mapping, modelling, and managing natural resources at various spatial scales. We believe, moreover, that it will prove its worth as a tutorial and reference source to anyone involved in the analysis of DEMs.

It is not our intention that this volume deliver an exhaustive synthesis of geomorphometry. A reader with a background in civil engineering, for example, will quickly note applications and technical areas that are under-represented or absent. This does not mean that we did not think it worthwhile to include them, but rather that other books are better suited to the task. Nonetheless, we hope that a diverse readership will come to regard our book as a worthwhile source of information on the methods and applications of modern geomorphometry. We offer the book not so much as a stand-alone achievement, but rather as part of an initiative to promote development of the science so that not only researchers in geomorphometry, but also the wider community of DEM users, will apply it wisely. We offer our apologies if we have inadvertently and unintentionally omitted anyone's contributions to geomorphometry.

We wish to thank our science reviewers, *Bodo Bookhagen* (Stanford University, School of Earth Sciences, Stanford, CA, USA), *Peter Burrough* (University of Utrecht, The Netherlands), *Ian S. Evans* (Durham University, Durham, UK), *Peter Fisher* (City University, London, UK), *John Gallant* (CSIRO Land and Water, Canberra, Australia), *Gerard B.M. Heuvelink* (Wageningen University and Research Centre, Wageningen, The Netherlands), *Robert A. MacMillan* (LandMapper Environmental Solutions Inc., Edmonton, AB, Canada), *Richard Pike* (U.S. Geological Survey, Menlo Park, CA, USA), *David Tarboton* (Utah State University, Logan, UT, USA), *Stephen Wise* (University of Sheffield, Sheffield, UK), and *Ole Wendroth* (University of Kentucky, Kentucky, US). Their numerous comments and suggestions for improving and extending various chapters have been invaluable in bringing this project to a successful conclusion.

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Every effort has been made to trace copyright holders. We apologize for any unintentional omissions and would be pleased to add an acknowledgment in future editions.

> Tomislav Hengl and Hannes I. Reuter Ispra (VA), July 2007

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Part I

# Concepts

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## Geomorphometry: A Brief Guide

R.J. Pike, I.S. Evans and T. Hengl

basic definitions  $\cdot$  the land surface  $\cdot$  land-surface parameters and objects  $\cdot$  digital elevation models (DEMs)  $\cdot$  basic principles of geomorphometry from a GIS perspective  $\cdot$  inputs/outputs, data structures & algorithms  $\cdot$  history of geomorphometry  $\cdot$  geomorphometry today  $\cdot$  data set used in this book

#### 1. WHAT IS GEOMORPHOMETRY?

*Geomorphometry* is *the science of quantitative land-surface analysis* (Pike, 1995, 2000a; Rasemann et al., 2004). It is a modern, analytical-cartographic approach to representing bare-earth topography by the computer manipulation of terrain height (Tobler, 1976, 2000). Geomorphometry is an interdisciplinary field that has evolved from mathematics, the Earth sciences, and — most recently — computer science (Figure 1). Although geomorphometry<sup>1</sup> has been regarded as an activity within more established fields, ranging from geography and geomorphology to soil science and military engineering, it is no longer just a collection of numerical techniques but a discipline in its own right (Pike, 1995).

It is well to keep in mind the two overarching modes of geomorphometric analysis first distinguished by Evans (1972): *specific*, addressing discrete surface features (i.e. *landforms*), and *general*, treating the continuous land surface. The morphometry of landforms *per se*, by or without the use of digital data, is more correctly considered part of *quantitative geomorphology* (Thorn, 1988; Scheidegger, 1991; Leopold et al., 1995; Rhoads and Thorn, 1996). Geomorphometry in this book is primarily the computer characterisation and analysis of continuous topography. A fine-scale counterpart of geomorphometry in manufacturing is *industrial surface metrology* (Thomas, 1999; Pike, 2000b).

The ground beneath our feet is universally understood to be the interface between soil or bare rock and the atmosphere. Just what to call this surface and its science of measurement, however, is less obvious. Numerical representation of the

 $<sup>^{1}</sup>$  The term, distinguished from morphometry in other sciences (e.g. biology), dates back at least to Neuenschwander (1944) and Tricart (1947).

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**FIGURE 1** Geomorphometry and its relation to source and end-user disciplines. Modified after Pike (1995).

*land surface* is known variously as *terrain modelling* (Li et al., 2005), *terrain analysis* (Wilson and Gallant, 2000), or the *science of topography* (Mark and Smith, 2004).<sup>2</sup> Quantitative descriptors, or measures, of land-surface form have been referred to as *topographic attributes* or *properties* (Wilson and Gallant, 2000), *land-form parameters* (Speight, 1968), *morphometric variables* (Shary et al., 2002), *terrain information* (Martinoni, 2002), *terrain attributes* (Pennock, 2003), and *geomorphometric attributes* (Schmidt and Dikau, 1999).

**REMARK 1.** Geomorphometry is the science of topographic quantification; its operational focus is the extraction of land-surface parameters and objects from digital elevation models (DEMs).

Despite widespread usage, as a technical term *terrain* is imprecise. *Terrain* means different things to different specialists; it is associated not only with land form, hydrographic features, soil, vegetation, and geology but also (like *topography*) with the socio-economic aspects of an area (Li et al., 2005). *Terrain*<sup>3</sup> also can signify an area of ground, a region... unrelated to *shape* of the land surface. The much used *terrain analysis* (Moore et al., 1991a; Wilson and Gallant, 2000) is confusing (unless preceded by *quantitative*), because it has long denoted qualitative (manual) stereoscopic photo- or image-interpretation (Way, 1973). Nor does the more precise *digital terrain modelling* (Weibel and Heller, 1991) escape ambiguity, as *terrain modelling* can infer measurement or display of surface heights, unspecified quantification of topography, or any digital processing of Earth-surface features.

<sup>&</sup>lt;sup>2</sup> The most frequent equivalents of *geomorphometry* in Google's online database appear to be *surface* or *terrain modelling*, *terrain analysis* and *digital terrain modelling* (Pike, 2002).

<sup>&</sup>lt;sup>3</sup> Terrain is from the Latin terrenum, which might be translated as "of the earth".

Additionally, in many countries (e.g. France, Spain, Russia, Slovakia) *relief*<sup>4</sup> is synonymous with morphology of the land surface (King et al., 1999). This usage is less evident in Anglophone regions (e.g. Great Britain, North America), where *relief*, usually prefixed by *relative* or *local*, has come to denote the difference between maximal and minimal elevation within an area (Partsch, 1911; Smith, 1953; Evans, 1979), "*low*" and "*high*" relief indicating small and large elevation contrasts respectively.<sup>5</sup>

To minimise confusion, the authors of this book have agreed to consistently use *geomorphometry* to denote the scientific discipline and *land surface*<sup>6</sup> to indicate the principal object of study. Digital representation of the land surface thus will be referred to as a *digital land surface model* (DLSM), a specific type of *digital surface model* (DSM) that is more or less equivalent to the widely-accepted term *digital elevation model*<sup>7</sup> (DEM).

An area of interest may have several DSMs, for example, surface models showing slope gradient or other height derivative, the tree canopy, buildings, or a geological substrate. DSMs from laser altimetry (LiDAR, light detection and ranging) data can show more than one *return surface* depending on how deep the rays penetrate. Multiple DLSMs are usually less common but can include DEMs from different sources or gridded at different resolutions, as well as elevation arrays structured differently from square-grid DEMs (Wilson and Gallant, 2000). Objects of the built environment are of course not part of the land surface and must be removed to create a true bare-earth DLSM.

*Digital elevation model* (DEM) has become the favoured term for the data most commonly input to geomorphometry, ever since the U.S. Geological Survey (USGS) first began distribution of 3-arc-second DEMs in 1974 (Allder et al., 1982). Even *elevation* is not unique as it can also mean surface uplift (e.g. the Himalayas have an *elevation* of 5 mm/year). However, the alternative terms are less satisfactory: *height* is relative to a nearby low point, and *altitude* commonly refers to vertical distance between sea level and an aircraft, satellite, or spacecraft. Thus *digital height model* and *altitude matrix* (Evans, 1972) are avoided here.

**REMARK 2.** The usual input to geomorphometric analysis is a square-grid representation of the land surface: a digital elevation (or land surface) model (DEM or DLSM).

In this book, DEM refers to a gridded set of points in Cartesian space attributed with elevation values that approximate Earth's ground surface (e.g. Figure 5, below). Thus, contour data or other types of sampled elevations, such as a triangular array, are not DEMs as the term is used here. "DEM" implies that elevation is available continuously at each grid location, at a given resolution. See Chapter 2 for a detailed treatment of topography and elevation models.

<sup>&</sup>lt;sup>4</sup> fren. *Topographie*, germ. *Relief*, russ. рельеф, span. *Relieve*.

<sup>&</sup>lt;sup>5</sup> This quantity is also known as *reliefenergie* (Gutersohn, 1932), particularly in Germany and Japan.

<sup>&</sup>lt;sup>6</sup> fren. *Surface terrestre*, germ. *Gelände*, russ. **земная поверхность**, span. *Topografía*. A term that became widely known through the morphometric work of Hammond (1964).

<sup>&</sup>lt;sup>7</sup> fren. Modèle numèrique de terrain, germ. Digitales Gelände Model, russ. цифровая модель рельефа, span. Modelo de elevación digital.

Finally, we define *parameter* and *object*, the two DEM-derived entities fundamental to modern geomorphometry (see, e.g., Mark and Smith, 2004). A *landsurface parameter*<sup>8</sup> is a descriptive measure of surface form (e.g. slope, aspect, wetness index); it is arrayed in a continuous field of values, usually as a raster image or map, for the same referent area as its source DEM. A *land-surface object*<sup>9</sup> is a discrete spatial feature (e.g. watershed line, cirque, alluvial fan, drainage network), best represented on a vector map consisting of points, lines, and/or polygons extracted from the square-grid DEM.

It is also important to distinguish parameters *per se*, which describe the land surface at a point or local sample area, from quantitative *attributes* that describe objects. For example, slope gradient at a given point refers only to its *x*, *y* location, whereas the volume of, say, a doline (limestone sink) applies to the entire area occupied by that surface depression; slope is a land-surface parameter, while depression volume over an area is an attribute of a land-surface object. Each of these quantities can be obtained from a DEM by a series of mathematical operations, or *morphometric algorithms*.

### 2. THE BASIC PRINCIPLES OF GEOMORPHOMETRY

#### 2.1 Inputs and outputs

The fundamental operation in geomorphometry is *extraction of parameters and objects from DEMs* (Figure 2). DEMs, i.e. digital land-surface models, are the primary input to morphometric analysis. In GIS (geographic information system) terms, a DEM is simply a raster or a vector map showing the height of the land surface above mean sea level or some other referent horizon (see further Section 2 in Chapter 2).

Geomorphometry commonly is implemented in five steps (Figure 2):

- 1. Sampling the land surface (height measurements).
- 2. Generating a surface model from the sampled heights.
- 3. Correcting errors and artefacts in the surface model.
- 4. Deriving land-surface parameters and objects.
- 5. Applications of the resulting parameters and objects.

Land-surface parameters and objects can be grouped according to various criteria. Parameters commonly are distinguished as primary or secondary, depending on whether they derive directly from a DEM or additional processing steps/inputs are required (Wilson and Gallant, 2000). In this book, we will follow a somewhat different classification that reflects the purpose and type of analysis. Three main groups of land-surface parameters and objects are identified:

- Basic morphometric parameters and objects (see Chapter 6);
- Parameters and objects specific to hydrology (see Chapter 7);
- Parameters and objects specific to climate and meteorology (see Chapter 8);

<sup>8</sup> fren. Paramètre de la surface terrestre, germ. Reliefparameter, russ. характеристика рельефа, span. Variable del terreno.
 <sup>9</sup> fren. Object de la surface terrestre, germ. Reliefobjeckt, russ. объект земной поверхности, span. Elemento del terreno.



**FIGURE 2** The operational focus of geomorphometry is extraction of land-surface parameters and objects from DEMs.

Basic parameters and objects describe local morphology of the land surface (e.g. slope gradient, aspect and curvature). Hydrological or flow-accumulation parameters and objects reflect potential movement of material over the land surface (e.g. indices of erosion or mass movement). The third group of parameters and objects is often calculated by adjusting climatic or meteorological quantities to the influence of surface relief.

A special group of land-surface objects — geomorphological units, *land elements* and *landforms* — receives its own chapter (Chapter 9). A landform is a discrete morphologic feature — such as a watershed, sand dune, or drumlin that is a functionally interrelated part of the land surface formed by a specific geomorphological process or group of processes. Each landform may be composed of several landform elements, smaller divisions of the land surface that have relatively constant morphometric properties.

**REMARK 3.** A landform element is a division of the land surface, at a given scale or spatial resolution, bounded by topographic discontinuities and having (relatively) uniform morphometry.

Recognition of landforms and less exactly defined tracts, commonly referred to as *land-surface types*, from the analysis of DEMs is increasingly important. Many areas of the Earth's surface are homogeneous overall or structured in a distinctive way at a particular scale (e.g. a dune field) and need to be so delineated (Iwa-hashi and Pike, 2007). In the special case of landforms extracted as "*memberships*" by a fuzzy classification algorithm, such forms can be considered to "*partake*" of a particular land-surface object — instead of directly mapping, say, a stream channel, we can obtain a "*membership value*"<sup>10</sup> to that landform.

#### 2.2 The raster data structure

Many land-surface representations, such as the background topography seen in video games and animated films, are modelled by mass-produced surface heights arrayed in some variant of the surface-specific *triangulated irregular network* (TIN) model (Blow, 2000; Hormann, 1969; see Chapter 2, Section 2.1). Most geomorphometric applications, however, use the square-grid DEM model. To be able to apply the techniques of geomorphometry effectively, it is essential to be familiar with the concept of a raster GIS and its unique properties.

Although the raster structure has a number of disadvantages, including a rectangular data array regardless of the morphology of the study area, large datastorage requirements, and under- and over-sampling of different parts of a diverse study area, it will remain the most popular format for spatial modelling in the foreseeable future. This structure is especially advantageous to geomorphometry because most of its technical properties are controlled automatically by a single measure: spatial resolution, *grid size* or *cell size*,<sup>11</sup> expressed as a constant *x*, *y* spacing (usually in metres) (Hengl, 2006).

In addition to grid resolution, we also need to know the coordinates of at least one grid intersection (usually marking the lower left-hand corner of the entire DEM array) and the number of rows and columns, whereupon we should be able to define the entire map (Figure 3). This of course assumes that the map is projected into an *orthogonal system* where all grid nodes are of exactly equal size and oriented toward cartographic North.

Accordingly, the small  $6 \times 6$ -pixel DEM in Figure 5 (see below) can also be coded in an ASCII file as an array of heights:

```
ncols 6
nrows 6
xllcorner 0
yllcorner 0
cellsize 10.00
nodata_value -32767
10 16 23 16 9 6
14 11 18 11 18 19
19 15 13 21 23 25
20 20 19 14 38 45
24 20 20 28 18 49
23 24 34 38 45 51
```

<sup>10</sup> Such a value has been designated by the rather clumsy term *channelness*.

<sup>11</sup> Cell size is a more appropriate term than grid size because grid size can also imply size of the whole grid.



**FIGURE 3** An orthogonal raster map can be defined by just five parameters: (a & b) number of rows and columns; (c & d) coordinates of the lower left corner and (e) cell size.

where ncols is number of columns, nrows is number of rows, xllcorner is the western edge of the map, yllcorner is the southern edge of the map, cellsize is grid resolution in metres, nodata\_value is the arbitrary value used to mask out locations outside the area of interest and 10, 16, 23, 16, 9, 6 are the elevation values in the (first) row. This is the standard format for ASCII grid files used by ESRI Inc. for its ArcInfo and ArcGIS software. It is necessary to define the initial point of the grid system correctly: there is a difference in *x*, *y* location of half the cellsize, depending on whether the first coordinate is at the lower left-hand corner of the lower left-hand grid cell (llcorner) or at the centre of that cell (llcenter).

**REMARK 4.** The principal advantage of a raster GIS over other spatial data structures is that a single measure — the cell or pixel size — automatically controls most technical properties.

#### 2.3 Geomorphometric algorithms

Performing morphometric operations within a raster GIS usually involves calculating intermediate quantities (over the same grid of interest) which are then used to compute the final output. Most morphometric algorithms work through the *neighbourhood operation* — a procedure that moves a small regular matrix of cells (variously termed a *sub-grid* or *filter window*) over the entire map from the upper left to the lower right corner and repeats a mathematical formula at each placement of this sampling grid.

Neighbouring pixels in a sampling window are commonly defined in relation to a central pixel, i.e. the location for which a parameter or an object membership is derived. In principle, there are several ways to designate neighbouring pixels, most commonly either by an identifier or by their position relative to the central