A BIBLIOGRAPHY OF GEOMORPHOMETRY
WITH A TOPICAL KEY TO THE LITERATURE AND AN
INTRODUCTION TO THE NUMERICAL CHARACTERIZATION
OF TOPOGRAPHIC FORM

by
Richard J. Pike

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# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>Land-surface quantification</td>
<td>5</td>
</tr>
<tr>
<td>The problem</td>
<td>5</td>
</tr>
<tr>
<td>Toward a solution</td>
<td>6</td>
</tr>
<tr>
<td>Morphometry demystified</td>
<td>7</td>
</tr>
<tr>
<td>Current practice</td>
<td>9</td>
</tr>
<tr>
<td>Implementation</td>
<td>16</td>
</tr>
<tr>
<td>The bibliography</td>
<td>17</td>
</tr>
<tr>
<td>Background</td>
<td>17</td>
</tr>
<tr>
<td>Purpose and scope</td>
<td>18</td>
</tr>
<tr>
<td>Subsets of the main list</td>
<td>19</td>
</tr>
<tr>
<td>Amendments</td>
<td>21</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>22</td>
</tr>
<tr>
<td>Bibliography</td>
<td>23</td>
</tr>
</tbody>
</table>

## ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Goals and applications</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Topical key to the literature</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>The DEM-to-watershed transformation</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cognate disciplines</td>
<td>8</td>
</tr>
</tbody>
</table>
A BIBLIOGRAPHY OF GEOMORPHOMETRY

WITH A TOPICAL KEY TO THE LITERATURE AND AN INTRODUCTION TO THE NUMERICAL CHARACTERIZATION OF TOPOGRAPHIC FORM

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Richard J. Pike

ABSTRACT

A compilation of over 2100 references provides one-source access to the diverse literature on geomorphometry, the quantification of land-surface form. The report also defines the discipline, describes its scope and practice, discusses goals and applications, and identifies related fields. The bibliography documents the current, computer-driven state-of-art of geomorphometry and furnishes the historical context for understanding its evolution. Most entries address at least one of ten aspects of the science—its conceptual framework, enabling technology, topographic data and their spatial ordering, terrain attributes in vertical and horizontal domains, scale dependence and self-organization of topography, redundancy of descriptive parameters, terrain taxonomy, and the interpretation of land-surface processes. A subset of some 350 references, divided into 49 topics that outline the field of geomorphometry in more detail, guides the reader into the longer, unannotated listing. Lastly, over 100 references trace the development and application of one of the discipline's outstanding new contributions: the DEM-to-watershed transformation.

Topography is perhaps the single most important land surface characteristic that determines the climatic, hydrologic and geomorphic regimes.

Isacks and Mouninis-Mark (1992)

INTRODUCTION

This report is a research bibliography on the numerical representation of topography, or geomorphometry, a technical field within the Earth sciences. (I use topography in the restricted sense of ground surface or terrain, excluding vegetation and the cultural landscape.) Also known simply as morphometry, this old and widely practiced specialty has been revitalized over the past 25 years by the digital computer and related developments. Geomorphometry serves both applied and basic ends, supporting society's use of technology as well as contributing to scientific understanding of natural processes (Table 1). The main applications of morphometry to technology include engineering, transportation, public works, and military operations. Morphometry for the interpretation of natural processes and events has two principal functions; it leads not only to new discoveries in Earth science, but also to application of those results for improving the condition of human settlement—most explicitly protection from environmental hazards and the management of natural resources.

I hope to address several issues by compiling a reference resource on geomorphometry. The first, and overriding, purpose is to improve access to the scattered writings of this diverse field. A related goal is to promote scholarship in understanding the development of the discipline and in
Table 1

Some Goals and Applications of Geomorphometry

I. UNDERSTAND NATURAL PROCESSES

A. Pure (primarily Earth) Science—discoveries in:

<table>
<thead>
<tr>
<th>Geomorphology</th>
<th>Geophysics</th>
<th>Meteorology</th>
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<tbody>
<tr>
<td>Geology</td>
<td>Soil Science</td>
<td>Oceanography</td>
</tr>
<tr>
<td>Hydrology</td>
<td>Climatology</td>
<td>Planetary Science</td>
</tr>
</tbody>
</table>

B. Applied Science—uses of new discoveries (A, above) to:

1. Evaluate natural hazards & reduce their effects:

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope failure</td>
<td>Inventory &amp; mapping</td>
</tr>
<tr>
<td>Wildfire</td>
<td>Zoning</td>
</tr>
<tr>
<td>Earthquake</td>
<td>Risk assessment</td>
</tr>
<tr>
<td>Flood</td>
<td>Mitigation</td>
</tr>
<tr>
<td>Coastal erosion</td>
<td>Prediction</td>
</tr>
<tr>
<td>Volcanic eruption</td>
<td>Benefit-cost analysis</td>
</tr>
<tr>
<td>Severe storm</td>
<td>Emergency response</td>
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<tr>
<td>Tsunami</td>
<td>Restoration</td>
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2. Develop & manage natural resources:

<table>
<thead>
<tr>
<th>Resources</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Inventory &amp; mapping</td>
</tr>
<tr>
<td>Soils &amp; arable land</td>
<td>Environmental protection</td>
</tr>
<tr>
<td>Vegetation &amp; forests</td>
<td>Engineering</td>
</tr>
<tr>
<td>Open space &amp; parks</td>
<td>Benefit-cost analysis</td>
</tr>
<tr>
<td>Minerals &amp; fuels</td>
<td>Reclamation</td>
</tr>
<tr>
<td>Wetlands</td>
<td>Commodity extraction</td>
</tr>
<tr>
<td>Wildlife</td>
<td>Depletion-modeling</td>
</tr>
</tbody>
</table>

II. SUPPORT TECHNOLOGICAL NEEDS OF SOCIETY

A. Engineering, Transportation, & Public Works:

<table>
<thead>
<tr>
<th>Cultivation</th>
<th>Vehicle design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbanization &amp; land use</td>
<td>Planning, siting &amp; design of:</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>Bridges, airports, canals, dams,</td>
</tr>
<tr>
<td>Navigation</td>
<td>Highways, irrigation, water supply</td>
</tr>
<tr>
<td>Waste disposal</td>
<td>Planetary-surface exploration</td>
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</tbody>
</table>

B. Military Operations:

<table>
<thead>
<tr>
<th>Concealment &amp; avoidance</th>
<th>Reconnaissance &amp; targeting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-country mobility</td>
<td>Weapons design &amp; deployment</td>
</tr>
<tr>
<td>Logistics &amp; engineering</td>
<td>Tactical &amp; strategic planning</td>
</tr>
</tbody>
</table>
citing its literature. Third, I have taken the opportunity afforded by this compilation to organize the science of geomorphometry—to identify its components and arrange them in a structure that is consistent with current research directions and applications (Table 2). The fourth objective is to foster a sense of unity within a field that is complex and fragmented and to provide its workers with a focus—a sense of place within science and technology. The fifth goal is to provoke new inquiries into the nature of topography, through the cross-fertilization of ideas that the diversity of this bibliography is intended to create. The sixth aim is to prompt colleagues to investigate the field’s related disciplines (Fig. 1) and activities (Table 2) for solutions to operational problems in topographic analysis. Seventh, I want to encourage the continuing development of computer software that implements new approaches and procedures in morphometry (for example, Table 3). My final goal is to call attention to the need for higher standards of accuracy in the mass-produced digital elevation data on which progress in the field depends so critically.

LAND-SURFACE QUANTIFICATION

The Problem

Form has lagged behind process in the quantitative understanding of the Earth’s surface and its evolution. Over the past few decades much progress has been made in describing agents of geomorphic change and how they work, even to the extent of modeling physical processes numerically (for example, Anderson, 1988; Phillips and Renwick, 1992). Representation of the topography itself, except for individual drainage basins (Horton, 1945; Stahler, 1964), has been less successful. Reasons for this include the great complexity of terrain, the resulting difficulty in describing it numerically, and some reluctance to abandon the qualitative approach that has long seemed adequate for much research and teaching. Obstacles to quantifying terrain must be overcome, however, for they restrict the role of topographic data in addressing important issues in science and technology that require information on land form. Most recent among such problems is the numerical description, or parameterization, of continuous land-surfaces, which is essential to understanding the regional distribution of precipitation (Tarboton, 1992) and other elements that contribute to new knowledge of synoptic meteorology and global climate (Henderson-Sellers and Dickinson, 1992; Isacks and Mougins-Mark, 1992).

Descriptions of continuous topography tend to be qualitative and subjective, because the prevailing nomenclature is verbal and nonunique. Such adjectives as hilly, steep, gentle, rough, and flat mean different things to different observers, depending on their experience and the scale of the landscape under scrutiny (Wolfgang, 1941; Frank and others, 1986). The common nouns mountain, plateau, hill, and plain are equally imprecise—an old shortcoming inherent in applying everyday language to technical questions. One result is that very different landscapes may be characterized in identical terms. Rolling hills in North Dakota, for example, does not mean the same thing as rolling hills in Tuscany, and neither resembles the rolling hills celebrated in songs of the Scottish Border country. Such confusion reflects several underlying issues. For example, just what are rolling hills? What makes them rolling to the eye and to the mind; what distinguishes them from non-rolling hills? How does an observer’s location, both on and above the ground surface, affect the perception of hills as rolling? And, for that matter, what is a hill and when is it not a hill but rather a ridge or a mountain? These questions, which are of great interest in applied linguistics and the psychology of cognition, are not trivial (Gibson, 1950, 1979; Hoffman, 1990; Graff, 1992).

The different shades of meaning that reside in qualitative terms greatly impede the communication of information about topography. The basic problem, even among experts familiar with landscapes worldwide, is this: language used to represent continuous terrain is not systematically
equated with measurable attributes of land form (Frank and others, 1986; Hoffman and Pike, 1992). Without such measures and an orderly taxonomy of form it is impossible, for example, to define rolling hills or to specify in exactly what respects the hills of Tuscany differ from those of North Dakota or the Scottish Border. More importantly, it is impossible to incorporate those differences, whatever they might be, into numerical models of terrain that can be related to spatial variation in climate and other natural phenomena, or to use topographic form effectively in related applications. Finally, without precise description of the what there can be no meaningful why—the operation of geomorphic processes at the Earth's surface cannot be explained convincingly in quantitative terms without measures of the resulting topographic forms. Such measures should be sufficiently comprehensive to provide a signature of process (Pike, 1988a, b), save in cases of convergence, or equifinality—where different processes and conditions yield similar landforms (Thorn, 1988).

Toward a Solution

The need for repeatable, and thus numerical, description of observations in many sciences has led to the measurement of shape, or morphometry. This approach has been particularly successful in such fields as biological systematics (Thompson, 1917; Bookstein, 1978; Warheit, 1992) and sedimentary petrography (Krumbein and Pettijohn, 1938; Marshall, 1987). Application of morphometry to the Earth's surface has come to be known as geomorphometry, geo-distinguishing this craft from its practice elsewhere, both within and outside of geology and geography. The term, which was simply morphometry in the early 20th century and previously orometry (Hettner, 1928; Beckinsale and Chorley, 1991), dates back at least to Tricart (1947); it has gained acceptance mainly through the work of Evans (1972) and Mark (1975a). Although a little awkward, the term is no more so than many others in the Earth sciences—for example, paleomagnetism. Lastly, geomorphometry is well established and nothing is to be gained by searching out an alternative.

Reduced to its analytic essentials, topography is just geometry and topology. Geometric measures have long been used to describe the three-dimensional form of topographic features that are expressed as points, lines, areas, and volumes in Euclidean space (Smith, 1935; Melton, 1958b; Wood and Snell, 1960a). However, Euclidean geometry vastly oversimplifies so complex a surface as continuous topography (Frank, 1988). Topologic parameters have been introduced more recently to describe sequential order, connectivity, and other non-Euclidean attributes that comprise the spatial arrangement of topographic features (Horton, 1945; Shreve, 1967; Mark, 1979a). Many measures of both types, some of them taken at several spatial scales, are required to effectively represent the shape of a terrain surface (Van Lopik and Kolb, 1959; Hammond, 1964a, b; Pike and Rozema, 1975). The geometry of basic elements—ridges, valleys, slopes, peaks, depressions, and passes—is captured by slope, curvature, and other derivatives of terrain height in both the vertical (Z) domain and in the horizontal (X, Y) domain. The topology of these elements is most frequently expressed as a hierarchy of channel links and nodes, ridges, and watersheds. Nonetheless, parameters of X, Y attributes other than those based on stream order are essential to fully describe the topology of landscapes—particularly where fluvial degradation is not the dominant process.

Two approaches to geomorphometry are often distinguished (Evans, 1972): specific—describing discrete features, or landforms, and general—describing continuous topography, or landscapes. Specific morphometry, which directly reflects geomorphic process, is comparatively well developed (Evans, 1987a; Jarvis and Clifford, 1990). Its application is most mature in the study of drainage basins, impact craters and volcanoes, and other landforms that are readily isolated in the landscape. Specific morphometry is less well developed for landforms that can be difficult to identify or delimit, such as drumlins, sand dunes,
cirques, and karst features (Evans and Cox, 1974). The practice of morphometry is most primitive for the general case, continuous topography, which least directly reflects geomorphic process and is commonly applied to line-of-sight (viewshed), terrain roughness, and other engineering problems. General geomorphometry today offers many challenges (Pike, 1988a; Pike, Acevedo and Card, 1989; Evans, 1990). Its research agenda includes the problem of nonstationarity (azimuth dependence) of much topography, ambiguity of guidelines for sampling terrain, the unknown degree of scale dependence of land form, and difficulties in describing the organization of continuous topography in the X,Y domain.

Morphometry Demystified

Geomorphometry has been defined as the science "which treats the geometry of the landscape" (Chorley and others, 1957, p. 138), but these few words are now inadequate. The computer revolution and related technology, exploration of the planets and Earth's seafloor, and developments in topology and in surface characterization since 1957 warrant an updated definition. The alternatives are many. They range from simply quantification of topography to numerical extraction and expression of the information content of terrain surfaces. Whatever the definition, geomorphometry is an emerging discipline of land-surface form that transcends method. It is not just a set of approaches and techniques, a toolbox for solving terrain-related problems in science and technology, but a research specialty of its own. Geomorphometry as a science is still immature. Although morphometry has predictive capability (Wood, 1967), it remains highly empirical and—like geomorphology (Cox and Evans, 1987; Rhoads and Thorn, 1993)—lacks unifying theory.

Much work lies ahead before a theory can be formulated for geomorphometry; two possible approaches are noted briefly here. One path is through geomorphology, perhaps the most closely allied discipline (Thorn, 1988). For example, a theory of morphometry might build formal geometric and topologic structures of the Earth's surface for geomorphology, in somewhat the same way that crystallography provides the geometric foundation for mineralogy. Such simple analogies as this would have to be developed much further and incorporate geomorphic processes. Geography offers an alternate path to morphometric theory, which might be based less on physical processes and laws and more on spatial properties and relations derived from graph theory (Bunge, 1962; Mark, 1979a). Such a theory for geomorphometry would require first a general theory of geographical space (King, 1969; Frank and others, 1986; Peuquet, 1988a) that could be implemented by computer (Frank, 1988; Dikau, 1990a).

Geomorphometry is evolving from a vaguely bounded and supportive role between various disciplines into a coherent academic field. However, it is still more derivative and interdisciplinary than primary and independent. Morphometry borrows from, interacts with or feeds back to, and furnishes information for longer-established areas of study, some of them marginal to the Earth sciences (Fig. 1). It is identified with many military and engineering applications (for example, Bekker, 1969). In the United States, morphometry is allied closely with surface hydrology, notably through work starting with that of Horton (1945) and more recently through the computer-partitioning of watersheds from matrices of terrain heights (Table 3; Tribe, 1992b). The field is recognized as a specialty within geology, geography, and geomorphology (Graf, 1988; Richards, 1990), as well as a subfield of digital cartography (Clarke, 1990).

The content of geomorphometry (Table 2) may be more familiar to Earth scientists as terrain analysis, quantitative geomorphology, or terrain modeling. Although none of these terms is synonymous or entirely correct, all three approaches to land-surface quantification overlap, and morphometry includes much of each field. Terrain analysis tends to be applied. Its several connotations—particularly military, engineering, or remote-sensing—often address such problems in general morphometry as the classification of continuous surfaces according to roughness
Sources for Approaches and Techniques


Applications of Analyses and Results

Terrain analysis also can be entirely qualitative and commonly incorporates attributes of landscape other than geometry of the surface—as in the mapping of land systems and similar types of natural units for land-use appraisal (Mitchell, 1973; Way, 1973). Quantitative geomorphology is a research discipline with a more strictly scientific focus. It generally interprets physical processes that create discrete features or orderly groups of them, notably drainage basins (Strahler, 1964; Morisawa, 1985) and impact craters (Baldwin, 1963; Pike, 1988c). As a rule, quantitative geomorphology involves specific morphometry and rarely addresses continuous topography, save in the context of regional landscape evolution.

**Terrain, or surface, modeling** describes recent applications of digital-cartographic technology to topographic data (Petrie and Kennie, 1990; Weibel and Heller, 1991). Because the term was rarely used to describe quantitative work predating the computer, it is not synonymous with geomorphometry. Terrain modeling commonly includes relief shading and other means of machine visualization, but it also indicates virtually any spatial ordering and geometric or topologic rendering of the land surface by computer (Dikau, 1990a). Terrain modeling is largely an automated implementation of general geomorphometry. Increasingly, however, such computer-based procedures as the delimitation of watersheds from elevation matrices (Table 3) are blurring the operational distinction between general and specific cases—between landscapes and landforms. Much of the future growth of geomorphometry, including development of its theory, almost certainly lies in what is now termed terrain modeling.

**Current Practice**

Although long established as a research endeavor, and more recently a discipline in its own right, geomorphometry remains diffuse and ill-defined. Much of the ambiguity arises from an ever-growing and diversifying technology that provides so many new ways to model topography by computer (Fisher and Lindenberg, 1989). To consolidate and more sharply focus the discipline of geomorphometry, I have identified 49 groups of activities or topics that characterize its current state-of-art and suggest a further ten-fold ordering of them (Table 2). This classification is not unique, for the topics could be arranged differently, some topics could be consolidated, and others could be added. I have simply found the structure of Table 2 to be helpful in my own research, in teaching, and in communicating with colleagues. The topics and relations shown in Table 1 and Figure 1, which outline some applications and cognate disciplines of geomorphometry, further aid in this attempt to define the field as it exists today.

The ten general areas in Table 2 are reviewed briefly here; the first four subject headings treat introductory topics and method. **Conceptual framework** sets forth an approach to the numerical representation of both discrete forms and continuous topography; it also addresses such complications of morphometry as its inherently spatial context. **Enabling technology** includes several computer-based techniques for the description of land form. Among these are different approaches to feature measurement as well as the most common means of machine visualization—relief shading. The heading **topographic data** emphasizes the production of information that is used to capture surface form, with special attention to the fidelity of digitized elevations obtained from contour maps. **Spatial ordering of topographic information** is concerned with designs for sampling terrain, often from contour maps, and with structuring the resulting elevations in ways that best describe surface form.

The remaining six topics in Table 2 cover the technical details of terrain representation and the applications of geomorphometry. **Derivatives of elevation in the vertical (Z) domain** include relief and slope angle, and are the most easily generated descriptors of topography. Such attributes of terrain in the X,Y (horizontal) domain as spacing and arrangement are more difficult to compute than Z-domain descriptors, but also capture much of the visual perception of surface form.
**Table 2**

A Topical Key to the Literature on Geomorphometry

---

**INTRODUCTION**

1. CONCEPTUAL FRAMEWORK

TOWARD A THEORY OF GEOMORPHOMETRY

Berry, 1968  
Dikau, 1990a  
Frank, Palmer, and Robinson, 1986  
Krcho, 1973, 1990  
Kugler, 1974  
Mark and Frank, 1989  
Thorn, 1988

PERCEPTION & COGNITION OF TOPOGRAPHY

Aloimonos, 1988  
Gibson, 1950, 1979  
Heinrichs and others, 1992  
Hoffman, 1990  
Hoffman and Pike, 1992  
Hsu, 1974  
Lay, 1991  
Savitt and others, 1992  
Tamura and others, 1978  
Young and Yamane, 1992

QUANTIFYING TOPOGRAPHY—NEEDS & CAPABILITIES

Clarke, 1966  
Greysukh, 1967  
Hammond, 1954a, 1965  
Horton, 1945  
Mark and Warnitz, 1982  
Pitty, 1982  
Richards, 1990  
Strahler, 1954a, 1992  
Wolffanger, 1941  
Wood and Snell, 1960a

LAND FORM VS. LANDFORMS: CONTINUOUS SURFACES VS. DISCRETE FEATURES

Evans, 1972, 1987a, 1990  
Hammond, 1965

Jarvis and Clifford, 1990  
Mark, 1975b  
Renwick, 1992  
Weaver, 1965

MORPHOMETRY AS ANALYTICAL CARTOGRAPHY

Chervyakov, 1990  
Clarke, 1990  
Dikau, 1990a, 1992  
Frank, Palmer, and Robinson, 1986  
Monkhouse and Wilkinson, 1971  
Peucker, 1972  
Tobler, 1976

**METHOD**

2. ENABLING TECHNOLOGY

DIGITAL TERRAIN (SURFACE) MODELING

Clarke, 1990  
Dikau, 1989, 1990  
McCullagh, 1988  
Petrie and Kennie, 1990  
Weibel, 1992  
Weibel and Heller, 1991

GEOGRAPHICAL INFORMATION SYSTEMS

Aronoff, 1989  
Burrough, 1986  
Carrara and others, 1991  
Cowen, 1988  
Davis and Dozier, 1990  
ESRI, 1992a  
Maguire, Goodchild, and Rhind, 1991  
Raper, 1989

REMOTE SENSING

Eppler and Farmer, 1991  
Franklin, 1991
Haralick and others, 1985
Leberl and others, 1991
Raggam and others, 1989
Sasowsky and others, 1991
Toriwaki and Fukumura, 1978
Wang and others, 1984

DIGITAL IMAGE-PROCESSING
Fabbri, 1984
Jensen, 1986
Ourmazd and others, 1989
Peuquet, 1979
Pike, Acevedo, and Thelin, 1988
Pike and Thelin, 1989

AUTOMATED RELIEF SHADING & PHOTOCLINOMETRY
Batson and others, 1975
Dubayah and Dozier, 1986
Elvhage and Lidmar-Bergström, 1987
Friedhoff and Benzon, 1991
Horn, 1981, 1990
Kennie and McLaren, 1988
Moellering and Kimerling, 1990
Muller and others, 1988
Thelin and Pike, 1991
Yoeli, 1967

AUTOMATED PATTERN RECOGNITION & FEATURE EXTRACTION
Argialas and others, 1988
Buttenfield, 1987
Greysukh, 1967
Haralick and others, 1985
Ivanov and Chalova, 1987
Lay, 1991
Nagao and Matsuyama, 1980
Pao, 1989
Riazanoff and others, 1990
Rosenfeld, 1981
Graff, 1992

EXPERT SYSTEMS & ARTIFICIAL INTELLIGENCE
Argialas and Narasimhan, 1988
Hadipriono and others, 1990
Mackay and others, 1992
Narasimhan and Argialas, 1989
Schenk and Zilberstein, 1990
Usery and others, 1988

COMPUTER ALGORITHMS & SOFTWARE PACKAGES
Barchi and Guzzetti, 1990
Cole and others, 1990
Collins and Moon, 1981
Dozier and Frew, 1990
ESRI, 1991b, 1992b
Evans, 1980
Franklin and Peddle, 1987
Grendler, 1976
Guth and others, 1987
Hobson, 1967
Jensen and Domingue, 1988
Nogami, 1985
Peddle and Franklin, 1990
Schaber, Pike, and Berlin, 1980
Thorn and others, 1987
Turner and Miles, 1968
Wolf, 1991b

3. TOPOGRAPHIC DATA

ACCURACY OF CONTOUR MAPS
El-Tahlawi and Rashad, 1991
Fahsi and others, 1990
Gugan and Dowman, 1988
Gustafson and Loon, 1982
Mahoney and others, 1991
Mark, 1983a

DIGITAL ELEVATION MODELS (DEM's) & DIGITAL LINE GRAPHS (DLG's)
I—CREATION & AVAILABILITY
Berry and others, 1988
Ellassal and Caruso, 1983
Hall and others, 1990
Hutchinson and Dowling, 1991
Kidner and Smith, 1992
McCulloch and Marinaro, 1988
Rinehart and Coleman, 1988
Schut, 1976
Sharif and Makarovic, 1989
Smith and Wessel, 1990
Topographic Science Working Group, 1988
Wolf and Wingham, 1992
Yoeli, 1986
DEM's & DLG's II—ASSESSMENT OF ERROR & QUALITY
Acevedo, 1991
Carter, 1989, 1992
Ebisch, 1984
Forstner, 1983
Guth, 1992
Hannah, 1981
Li, 1992
Östman, 1987
Pan, 1989
Polidori and others, 1991
Theobald, 1989
Theobald and Goodchild, 1990
USGS, 1988

ADVANCED TECHNIQUES OF DATA ACQUISITION
Björnsson, 1988
Brozena and others, 1992
Evans and others, 1992
Gardner, 1992
Gugan and Dowman, 1988
Krabill and others, 1984
Leberl and others, 1991
Marks and others, 1993
Raggam and others, 1989

4. SPATIAL ORDERING OF TOPOGRAPHIC INFORMATION
SAMPLE DESIGNS TO EXTRACT DATA FROM CONTOUR MAPS
Ansoult, 1989
Carstensen, 1990
Richards, 1990
Maling, 1989
Mark, 1975b
Ming, 1992
Snell, 1961
Strahler, 1956
Wood, 1967
Wood and Snell, 1960a

CARTOGRAPHIC DATA STRUCTURES I—RASTER & QUADTREE
Cebrian and others, 1985
Chen and Tobler, 1986
ESRI, 1991a
Ibbs and Stevens, 1988

Maguire, Kimber, Barry, and Chick, 1991
Samet, 1990
Shaffer, 1988

CARTOGRAPHIC DATA STRUCTURES II—SURFACE-SPECIFIC
Faldidieno and Pienovi, 1990
Frank, Palmer, and Robinson, 1986
Mark, 1979b
Peucker and Chrisman, 1975
Thapa, 1988
Wolf, 1991a

THE TRIANGULATED IRREGULAR NETWORK (TIN)
DeFloriani and others, 1986
ESRI, 1991b
Goodrich and others, 1991
Lee, 1991b
McKenna, 1986
Mirante and Weingarten, 1982
Peucker, Fowler, Little, and Mark, 1978
Plews and Clarke, 1990
Theobald and Goodchild, 1990

CHARACTERIZATION

5. Z-DOMAIN ATTRIBUTES
ELEVATION & SOME OF ITS DERIVATIVES
Clarke, 1966
Evans, 1980
Mark, 1975a
Ohmori and Hirano, 1984
Pike and Wilson, 1971
Stearns, 1967
Strahler, 1952
Tanner, 1959, 1960

LOCAL (RELATIVE) RELIEF
Ahnert, 1984
Drummond and Dennis, 1968
Ohmori, 1978
Pike, Acevedo, and Card, 1989
Wood, 1967
Zakrzewska, 1967
### ANGLE OF SURFACE SLOPE

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<th>Reference</th>
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<tr>
<td>Agopova, 1965</td>
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<td>Ahnert, 1970a</td>
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<td>Blong, 1975</td>
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<tr>
<td>Mark, Newman, and Brabb, 1988</td>
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<td>Moore and Mark, 1986</td>
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<td>O'Neill and Mark, 1987a</td>
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<td>Pfitz, 1968</td>
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<td>Speight, 1971</td>
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<td>Strahler, 1956</td>
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<td>Young, 1972</td>
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### CURVATURE OF SLOPE IN PROFILE

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<tr>
<td>Carrara and others, 1978</td>
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<td>Heerdegen and Beran, 1982</td>
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<td>Papo and Gelbman, 1984</td>
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<td>Pike, 1988a</td>
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<td>Troeh, 1965</td>
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### 6. X,Y-DOMAIN ATTRIBUTES

#### AZIMUTH (ASPECT) OF TOPOGRAPHIC FEATURES

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<tr>
<th>Reference</th>
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<tr>
<td>Abdel-Rahman and Hay, 1981</td>
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<tr>
<td>Dale and Ballantyne, 1980</td>
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<tr>
<td>Evans, 1977b</td>
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<tr>
<td>Gordon, 1981</td>
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<td>Jones, 1968</td>
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<td>Wadge, 1988</td>
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<td>Wadge and Cross, 1988</td>
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<td>Williams, 1974</td>
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#### LAND-SURFACE CURVATURE IN PLAN

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<tbody>
<tr>
<td>Chang and Toebes, 1970</td>
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<td>Evans, 1972, 1980</td>
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<tr>
<td>Snow, 1989</td>
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<td>Troeh, 1965</td>
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#### PLANIMETRIC SHAPE OF TERRAIN FEATURES

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<tr>
<td>Jarvis, 1976</td>
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<td>Komar, 1984</td>
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<td>LaGro, 1991</td>
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<tr>
<td>McArthur and Ehrlich, 1977</td>
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<td>Ongley, 1970</td>
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<tr>
<td>Piotrowski, 1989</td>
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<tr>
<td>Van Lopik and Kolb, 1959</td>
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<td>Whalley and Orford, 1989</td>
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### TERRAIN TEXTURE

#### I—SPACING & FREQUENCY

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<tr>
<th>Reference</th>
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<tr>
<td>Dolan and others, 1974</td>
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<td>Gregory and Gardiner, 1975</td>
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<td>Hallet, 1990</td>
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<td>Haralick, 1978</td>
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<td>Hill, 1973</td>
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<td>Howard, 1992</td>
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<td>Lancaster, 1988</td>
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<td>Mulla, 1988</td>
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<tr>
<td>Pike and Rozema, 1975</td>
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<td>Tarboton and others, 1992</td>
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#### II—ARRANGEMENT (PATTERN)

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<tr>
<td>Anderson, 1987</td>
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<td>Eppler and Farmer, 1991</td>
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<td>Franklin and Peddle, 1987</td>
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<td>He and Wang, 1990</td>
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<td>Hsu, 1978</td>
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<td>Mark, 1988</td>
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<td>Rossbacher, 1986</td>
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<td>Trifonov and Shults, 1990</td>
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<td>Vincent, 1987</td>
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#### TOPOLOGY OF CHANNELS AND OTHER ELEMENTS OF FORM

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<tr>
<td>Abrahams, 1987</td>
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<td>Bras and Rodriguez-Iturbe, 1989</td>
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<td>Hadipriono and others, 1989</td>
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<td>Haynes, 1977</td>
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<tr>
<td>Howard, 1990a</td>
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<td>Mark, 1979a, 1988</td>
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<td>Shreve, 1975</td>
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<td>Warntz, 1975</td>
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<td>Werner, 1991</td>
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### 7. SCALE DEPENDENCY & SPATIAL SELF-ORGANIZATION

#### VARIATION OF LAND FORM WITH SPATIAL SCALE

<table>
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<th>Reference</th>
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<tr>
<td>Church and Mark, 1980</td>
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<td>Frank, Palmer, and Robinson, 1986</td>
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<td>Hallet, 1990</td>
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<tr>
<td>Lettau, 1967</td>
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<td>Montgomery and Dietrich, 1992</td>
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8. REDUNDANCY OF TERRAIN PARAMETERS

MEASUREMENT OF COVARIANCE

Engstrom, 1989
Evans, 1972, 1984a
Gordon, 1977
Gray, 1961
Mark, 1975a
Melton, 1958b
Pike and Wilson, 1971

SORTING OUT INDEPENDENT DESCRIPTORS

Ebisemiju, 1979b
Evans, 1984a
Miller and others, 1990
Pike, 1974, 1988b
Wong, 1963

RESULTS & APPLICATIONS

9. TERRAIN TAXONOMY

CLASSIFICATION SCHEMES & THE GEOMETRIC SIGNATURE

Demek, 1972
Hammond, 1954a
Mather, 1972
Parry and Beswick, 1973
Pike, 1988a
Schreier and Lavkulich, 1979
Speight, 1976
Van Lopik and Kolb, 1959

TOPOGRAPHIC TYPES & TOPOGRAPHIC REGIONS

Beckinsale and Chorley, 1991
Dikau, Brabb, and Mark, 1991
Eyles, 1971
Hammond, 1964a, b
Krasnovskaja, 1988
Mather and Doornkamp, 1970
Scott and Austin, 1971
Speight, 1968, 1974
Wood and Snell, 1960a
TERRAIN EVALUATION & LAND SYSTEMS

Burrough, 1989
Isachenko, 1973
Mitchell, 1973
Stewart, 1968
Townshend, 1981
Way, 1973

ENGINEERING CATEGORIZATION OF TOPOGRAPHY

Bekker, 1969
Chiou and others, 1992
Costes and others, 1972
Fisher, 1991b
Goldberg, 1962a
Hibler, 1975
Petrie and Kennie, 1990
Rowan, McCauley, and Holm, 1971
Rozema, 1969
Tsipis, 1975
Tunnard and Pushkarev, 1963
Wentworth, Ellen, and Mark, 1987

10. INTERPRETATION OF SURFACE-SHAPING PROCESSES

SURFACE HYDROLOGY I—DRAINAGE BASIN MORPHOMETRY

Abrahams, 1984
Band and others, 1991
Gardiner, 1982a
Gardiner and Park, 1978
Howard, 1990a, b
Patton, 1988
Strahler, 1964, 1992
Zâvoianu, 1985
Zecarias and Brutsaert, 1985

SURFACE HYDROLOGY II—MODELING CHANGES IN THE GLOBAL ENVIRONMENT

Committee on Global Change, 1990
Davis and others, 1992
Dyer and Vinogradov, 1990
Henderson-Sellers and Dickinson, 1992
Isacks and Mouginiis-Mark, 1992
Lettau, 1967
Tarboton, 1992
Young and Pielke, 1983

SURFACE HYDROLOGY III—THE AUTOMATED DEM-TO-WATERSHED TRANSFORMATION

Tribe, 1992b (review paper)
(Table 3 has > 100 more references)

TOPOGRAPHY SHAPED BY NON-FLUVIAL PROCESSES

Carrara and others, 1982
Dolan and others, 1977a
Evans, 1977b, 1987b
Fox and Hayes, 1985
Håkanson, 1978
Lancaster, 1988
Mills and Starnes, 1983
Mock and others, 1972
Morhange, 1992
Pike, 1974
Piotrowski, 1989
Rentsch and others, 1990
Sauchyn and Gardiner, 1983
Silva and others, 1992
Smith, 1988

MODELING & SIMULATION OF PROCESS

Anderson, 1988
Band and others, 1991
Craig, 1980, 1989
Hugus and Mark, 1984
Mayer and others, 1981
McEwen and Malin, 1989
Toppe, 1987
Vertessey and others, 1990

OTHER APPLICATIONS RELATED TO GEOMORPHOLOGY

Aniya, 1985
Brabb, 1987
Burbank, 1992
Carrara and others, 1978
Chorowicz and others, 1991
Colleau and Lenôtre, 1991
Cook and others, 1988
Elmes and others, 1991
Morris, 1991
Norton and Sorenson, 1989
Simpson and Anders, 1992
Tinkler, 1971
Zachar, 1982
These spatial properties do not necessarily require elevation data. Topography differs in shape with level of generalization, or scale, and the degree of scale dependency and spatial self-organization is itself a key descriptor of form. Many measures may describe the same attribute of form; such redundancy of terrain parameters can be sharply reduced through correlation and multivariate analysis. Systems for terrain taxonomy, particularly in continuous topography, are a major goal of geomorphometry. Many classification schemes address numerical problems in the interpretation of land-surface processes from land form, including those in surface hydrology and the geomorphology of landforms other than drainage basins.

All ten general categories in Table 2 are active areas of research, but several of them focus on two broad, overlapping activities that have long been central to geomorphometry—developing new techniques of analysis and testing descriptive parameters. Operational techniques often are adapted from allied disciplines (Fig. 1; Table 2, mainly topics 2, 4, and 8). They include roughness analysis, line-of-sight (viewshed) modeling, network analysis, slope-frequency statistics, altimetric analysis, numerical taxonomy, spectral analysis, multivariate statistics, nearest-neighbor analysis, various types of sampling from both profiles and matrices, texture analysis, machine visualization and its complement shape-from-shading (photoclinometry), topologic modeling, signature analysis (fingerprinting), percentage hypsometry, and volumetric analysis. The parameters of form that have been found effective for abstracting natural topography are the subject of much current experimentation (Table 2, mainly topics 5-7). These measures describe various properties of elevation, relief, slope, curvature in plan and profile, spacing, direction and strength of aspect (azimuth), alignment (including parallelism), feature complexity and connectivity, degree of randomness, and scale dependency.

The uses for geomorphometry (Table 1) continue to multiply as computer technology advances and more digital data become available. Applications range from watershed management, measuring road and runway roughness, missile targeting, planetary and deep-sea exploration, and assessing soil erosion to meteorological modeling, quantifying cross-country mobility, mapping eco-regions, planning recreational land-use, and siting installations for microwave transmission. Most recently, morphometry has been adapted to regional tectonics (Burbank, 1992). Combinations of morphometric data with nontopographic information, from remote sensing and other cartographic sources, are especially powerful (Franklin, 1987a). One of the most successful of these combined applications has been the spatially-based study of natural hazards—particularly the recognition, prediction, and risk-assessment of slope failure from digital terrain data (Lied and Bakkehei, 1980; Carrara, 1983a; Aniya, 1985; Kobashi and Hirano, 1985; Brabb, 1987; Bernknopf and others, 1988; Pike, 1988a, Carrara and others, 1991; Mark, 1992; Ellen and others, 1993).

Implementation

Some of the issues in terrain quantification currently addressed by geomorphometry may be old (Wolfanger, 1941; Bekker, 1969; Chorley, 1972), but the enabling technology is new. The high-speed digital computers, analytical algorithms, input/output and communications devices, and large sets of topographic data that drive current research were unknown just 25 or 30 years ago. The resulting innovations in such related specialties as digital cartography, computer graphics, and geographic information systems (GIS) have revolutionized morphometry. The crucial improvement has been in the speed and volume of data processing. Large tracts of continuous topography can now be described in detail rather than characterized from a few samples; promising techniques and parameters can now be tested and evaluated rapidly, and for virtually any number of terrain types. As a result, progress in specific and especially in general geomorphometry has greatly accelerated. These computer-driven advances have led to new ways to represent topography (Goodchild and Mark,
1987; Clarke, 1990; Moore, 1991) as well as greater variety in the applications of morphometry (Burrough, 1986; Petrie and Kennie, 1990; Maguire and others, 1991b).

Progress in information technology promises to sustain the current vitality of geomorphometry. Through image processing, spatial statistics, machine visualization, and pattern recognition, the digital-computer revolution has laid the necessary foundation for future contributions in the field. New developments in morphometry are being implemented in such allied disciplines as remote sensing (Haralick, 1983), planetology (Leberl and others, 1991), oceanography (Fox and Hayes, 1985), and climatology (Henderson-Sellars, 1992; Tarboton, 1992). One problem at the frontier of current research in geomorphometry is the automated parsing and classification of continuous topography at different scales. Applicable techniques include knowledge-based recognition and extraction of specific features by computer (Chorowicz and others, 1989; Falcidieno and Spagnuolo, 1990). Improved description of spatial patterns and their analysis, notably by fuzzy-set logic or neural networks, promise to contribute to solving this problem and others (Narasimhan and Argialas, 1989; Sui, 1992).

The chief impediment to a wider practice of geomorphometry has always been the slow capture of data through manual measurement of topography, usually on contour maps (Raisz and Henry, 1937; Chapman, 1952; Strahler, 1956). This problem is being eliminated by the mass production of large matrices and networks of terrain heights, digital elevation models (DEM's) or digital terrain models (DTM's) (Case, 1978). The square-grid DEM was first implemented by computer in the late 1950's by Charles Miller and his colleagues in the department of civil engineering at MIT (Roberts, 1957), but its early applications were largely military (Noma and Misulia, 1959; Horton and others, 1962; Boehm, 1967). Soon adapted to civilian engineering and Earth science in limited applications (for example, Hobson, 1967; Tobler, 1969a; Pike and Wilson, 1971), the grid DEM was first thoroughly explored for its potential value to morphometry by Evans (1972, 1979, 1980). Today, little morphometric work is attempted without DEM data. Despite much progress, however, shortcomings in the quality of DEM's remain (Theobald and Goodchild, 1990; Acevedo, 1991) and DEM coverage of many parts of the world is either lacking or prohibitively expensive (Wolf and Wingham, 1992). Recent developments in remote-sensing technology should, in time, lead to removal of these obstacles (Evans and others, 1992).

THE BIBLIOGRAPHY

Background

The rapid growth and diversification of geomorphometry have created serious problems of information retrieval. The literature has become so heterogeneous and scattered that it is impossible to command the subject by consulting just a few key serials in geology or geography. Early work, defined here as anything published before World War II, appeared almost exclusively in a few European journals of geography (Smith, 1935; Neuenschwander, 1944). Such ease of access has not prevailed since the war. The still-evolving body of writing on morphometry is shared among increasing numbers of edited collections and symposium volumes, textbooks, technical reports, and scores of serials in the Earth sciences and related areas (Figure 1). Prolific contributors include the rapidly growing fields of digital cartography, remote sensing, spatial modeling, and computer graphics.

Much research on morphometry is inaccessible because its mission-oriented, commonly military, origin was not conducive to publishing in the open literature. This body of material is large because so much of modern geomorphometry is the product of the Cold War (1946-1991) and its offshoot, the Apollo Moon-landing program (1960-1972). (The open literature resulting from such work reveals a virtual who's who in geomorphometry, including Strahler, Melton, Hammond, Wood, Tobler, Evans,
Peucker, and David Mark. See Pruitt, 1979.) Major contributions to the field reside in the "gray literature", limited-distribution and in-house documents of military and other governmental agencies (particularly NASA) and their outside contractors (Peltier, 1953 and 1956; Hammond, 1958; Wood and Snell, 1960a; Mays, 1966; Davis, 1969). Most of this material is unclassified but is not well known to the newer students of morphometry and, in any case, is not readily accessible to them. To my knowledge, no interdisciplinary list of these government-sponsored works has been compiled previously.

Bibliographies on various aspects of geomorphometry have been published, but none of them is both current and has the great breadth required for research in the field today. Perhaps the most useful single source is the volume of Goudie and others (1990), in particular the section on morphometry edited by K.S. Richards. However, it is oriented toward geomorphology rather than engineering applications. Once the best, if difficult to find, Neuenschwander (1944) now is useful only as a historical source. The compilations by Carr and Van Lopik (1962, 1963) also are dated and hard to locate, as is the survey of early Russian work by Bocharov and Nikolayev (1957). Helpful reference lists, both on overviews of the subject and on its individual facets, are appended to more recent research papers, literature reviews, or monographs. Among these are Clarke (1966), Zakrzewska (1967), Stewart (1968), Bekker (1969), Salisbury (1971), Hormann (1971), Chorley (1972), Evans (1972, 1979), Mitchell (1973), Speight (1974), Pike and Rozema (1975), Mark (1975a), Horn (1981), Morisawa (1985), Burrough (1986), McCullagh (1988), Thorn (1988), and Petrie and Kennie (1990).

Purpose and scope

The bibliography included in this report addresses the problems of information-retrieval just described. It provides access to the entire field of geomorphometry by collecting representative citations of its dispersed and varied writings into a single source. The alphabetized list of over 2100 entries, dating from the late 18th century, is current through 1992. It emphasizes recent work; 1993 abstracts indicate some of the newest research trends. The need for such a compilation, as well as for the conceptual organization of the various elements of geomorphometry, became especially evident to me in 1988 while preparing the syllabus for a four-week summer course on the subject. The 49 subheadings in Table 2 are the latest iteration of that syllabus, which also served as the outline of a study guide for the course the following year. The literature search culminating in this report began shortly after that second course. It has been a part-time endeavor. The resulting bibliographic entries are cited largely, but not entirely, in the format of the U.S. Geological Survey. Some citations are incomplete and others are irregular in format; these flaws reflect the occasional use of secondary sources and the short time available for the project.

The variety of references reflects the great diversity of geomorphometry. Citations range from abstracts to long books, include routine applications as well as outstanding contributions to technique, and vary from obscure to celebrated and from trivial to profound. To encourage different approaches to problems in morphometry, I have referenced related studies from such peripheral fields as tribology (the study of abraded metal surfaces), meteorology, agricultural and military engineering, planetary-surface exploration, and psychologic (Fig. 1). Basic works from the growing literature on geographic information systems (GIS) and related advances in computer technology and digital cartography also are included. The listing is good on the extraction of digital elevations from contour maps, and other concerns of data capture, although technological advances should soon render much of this material obsolete. Such recent developments in terrain representation as fractal geometry (Mark and Aronson, 1984; Xia and others, 1991b) and harmonic analysis (Pike and Rozema, 1975; Mulla, 1988) are well covered. The listing is biased somewhat toward geomorphology and is perhaps weakest on civilian applications in engineering.
The bibliography includes as much U.S. Government "gray literature" on morphometry as I have been able to locate without a prolonged search. I knew of some of this material from my early work with Walter F. Wood at the U.S. Army Quartermaster Research and Engineering Center (Wood and others, 1962) and at Cornell Aeronautical Laboratory (Pike, 1964). Other references are familiar to me from participation in the NASA Apollo program, during the development of design criteria for the lunar roving vehicle (Pike, 1969). Many documents came from the estate of Walter Wood. Comparable material from other governments is poorly known to me and little of it is included in the bibliography. Although numerous military-sponsored documents are cited, many more applications of terrain intelligence to military doctrine and tactics are not generally available; none of this classified material is given here.

Emphasis of the bibliography is on general geomorphometry, the form of continuous topography. I have been more selective for specific geomorphometry, which addresses the shape of landforms—discrete units of topography shaped by known or likely physical processes. The quantification of landforms per se is well treated in the literature of geology and geomorphology. Accordingly, only a small fraction of the vast body of writing on hydraulic geometry and the morphometry of drainage basins is included here; that material is well accessed by other recent surveys (Gardiner, 1982a; Zăvoianu, 1985; Howard, 1990a, b). For similar reasons, my referencing of slope-profile analysis only samples the available information (Pitty, 1968; Young, 1972; Cox, 1990). I have ignored much of the large literature on impact craters—the most symmetric and easily measured of all landforms, among the first to be treated quantitatively (Schröter, 1791), and my own area of specialization (Pike, 1974, 1977, 1988c; Pike and Spudis, 1987). The listing is similarly thin on the morphometry of such well defined features as volcanoes (Pike, 1978b), drumlins (Piotrowski, 1989) and sand dunes (Breed and Grow, 1979), although some recent references to the literature on those and other landforms are provided (Table 2).

The bibliography is idiosyncratic in several further respects. English-language publications predominate, although I have attempted a token representation of the large non-English literature (for example, references in Krcho, 1990). I have neither seen nor read many of the obscure sources, especially old works and those in languages other than English, and in such cases I have relied on existing bibliographies (for example, Bocharov and Nikolayev, 1957; Hormann, 1971; Kugler, 1974), even at the risk of perpetuating incomplete or incorrect citations. In this respect I have thought it more helpful to be inclusive than exclusive. Extensive reference lists are already available for some sub-specialties (for example, relief shading; Horn, 1981; Horn and Brooks, 1989), and I have only sampled these. My bibliography includes much historical material, even though it is now technically obsolete, so that students may trace the development of thought and practice in the field. Some entries, such as those on statistics and numerical taxonomy or on evolution of the digital computer and its applications, are not wholly germane to morphometry. However, they contain interesting background, describe provocative analogies to terrain, provide helpful examples or teaching material, or simply offer food for thought. Although I have touched on many facets of geomorphometry and have tried to omit no important works, the listing makes no pretence to completeness. It thus remains something of a browser's choice.

Subsets of the main list

The bibliography is not annotated or subdivided by topic. These shortcomings are partly offset by the structured sample of some 350 references in Table 2. This selection provides an up-to-date introduction to each of the 49 sub-fields and activities within geomorphometry as well as guidance in pursuing further study from entries in the main listing. The topics in Table 2 overlap considerably, and few of the references fit comfortably in only one category. A similar
Table 3

Evolution of Research on the DEM-to-Watershed Transformation

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<tr>
<th>Year</th>
<th>Authors</th>
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<tr>
<td>1972</td>
<td>Natarajan, 1972 Sprunt, 1972</td>
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<td>1978</td>
<td>Moon, 1978</td>
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<tr>
<td>1981</td>
<td>Collins and Moon, 1981</td>
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<tr>
<td>1993</td>
<td>Chorowicz and others, 1993 Garbrecht and Martz, 1993 Helmlinger and others, 1993</td>
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</table>
ordering of all 2100-odd entries in the main listing would warrant additional, more specialized, topics. Most references in Table 2 are published in the open literature and have good bibliographies that provide further access to the specialized literature and cite important, but older or less available, works. Because Table 2 is deliberately biased toward recent publications in each category, some old classics are absent (Wentworth, 1930; Smith, 1935; Neuenschwander, 1944). Other major contributions to morphometry are excluded from Table 2 because they are unlikely to be found in all but specialized or research collections and large libraries (for example, Hammond, 1958; Mark, 1977; Evans, 1979; Kundert, 1988).

Some elements of geomorphometry are particularly important now, and their literature warrants special attention. These fast-evolving topics include the triangulated irregular network, or TIN (Kumler, 1990; Lee, 1991b), fractal modeling of topography (Polidori and others, 1991; Klinkenberg, 1992), and the automatic extraction of terrain features from DEM's and digital images by such advanced techniques as pattern recognition (Chorowicz and others, 1989; Lee and others, 1992). To exemplify the evolution of one of these topics, I have attempted a comprehensive listing for the automated DEM-to-watershed transformation—an area so active that the resulting list (Table 3) is already dated. Table 3 also omits a few references that describe the automated extraction of drainage networks using digital images instead of DEM’s (Toriwaki and Fukumura, 1978; Haralick and others, 1985).

The DEM-to-watershed transformation (Table 3) is a computationally intensive procedure that creates a network of surface-specific lines (ridges and drains) from a matrix of square-grid elevations and delimits areas (drainage basins). Independent, parallel work on the problem converged about 1982 (Marks and others, 1983, 1984). Subsequent enhancements compute a suite of geometric descriptors for each basin (Majure and Eash, 1991). The transformation is important because it fundamentally reorganizes topographic information, from continuous terrain into a mosaic of landforms, thus enabling much topography to be analyzed by the techniques of specific rather than general morphometry. The procedure can yield good results in topography that has sufficient relief to define the fluvial net unambiguously from a DEM. It is less successful in glaciated, eolian, karst, and other landscapes that lack well integrated drainage. To work properly the technique also requires a closely spaced DEM of good quality, particularly in areas of low relief (Martz and Garbrecht, 1992). Over 100 references in Table 3 trace this recent breakthrough in digital cartography from inception (Natarajan, 1972; Sprunt, 1972) to its practical application (Band and others, 1991; Blaszczynski, 1992) and its incorporation into both commercial and public-domain software (U.S. Army, 1991; ESRI, 1992b). Tribe (1992b) offers a good recent review of the procedure and discusses many of the references in Table 3.

Amendments
Incorrect and incomplete citations of the literature—resulting from failure to consult original works, carelessness in manuscript preparation, or typesetting errors—are an irritating fact of life. They are especially annoying in geomorphometry because much of this diverse literature is unfamiliar to specialists. I encountered many such errors in my survey of the discipline and have tried not to perpetuate them. However, mistakes always enter a listing of the size and detail presented here even when, as in this case, all entries were collected by one person and compiled in a computer file that was repeatedly checked and updated. Although effort has been made to assure that the references are correct, instances of the first two types of error cited above certainly remain and are my responsibility. I apologize for them and hope they are not too many or unduly misleading. Mistakes and omissions that are found by readers should be called to my attention so that corrections can be released in an addendum or in a more formal publication of the bibliography. Suggestions for revision or improvement in the arrangement of sub-topics within geomorphometry (Table 2) also are solicited.
Some voids remain in the bibliography and most of them reflect the limited time available for the project. Filling one such gap, on the military applications of morphometry, would also require access to sources that are closed. Although the end of the Cold War may lead to declassification of material from that period, government agencies and their civilian contractors commonly destroy restricted documents as they become obsolete (for example, Cornell Aeronautical Laboratories). However, such outdated writings can be valuable in tracing the history of geomorphometry and should be made public. Even office correspondence may be significant (for example, Groenewold, 1962). Lastly, comparable research in morphometry almost certainly was pursued by military agencies of former Warsaw Pact nations, especially the Soviet Union. This facet of geomorphometry, which would be of historical and probably substantive value, remains unknown to me save for possibly related civilian and academic references in Krcho (1990).

I welcome additions to this bibliography from its users. Again, the emphasis should be on general rather than specific morphometry. Entries in languages other than English are especially wanted, if accompanied by a translation of the citation (particularly for languages in non-Roman characters). To ensure accuracy and reduce ambiguity, please send reprints or photocopies of proposed additions rather than just the citations, if at all possible. However, I can entertain new entries if just the following information is provided:

1. photocopy of title page, or
   * title of the work, and
   * the name(s) of author(s); surname
     plus two initials (or, if one
     given name, then spelled out)

2. year of publication

3. the exact and complete citation of serial or other form of publication (book, conference proceedings, and so forth), including volume number, issue number, and inclusive page numbers. For meetings give location and dates; for books give name of city and publisher.

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