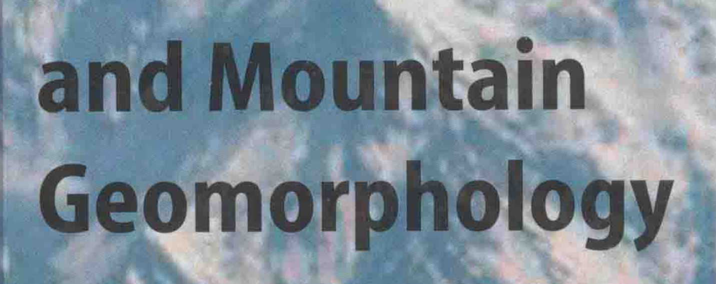
Geographic Information Science and Mountain Geomorphology



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and
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Preface

The relatively recent emergence of GIT is playing a significant role in the geosciences. The increasing capabilities of computers and GIS software, and availability of spatial and temporal data, have enabled Earth scientists to study mountain systems in new ways and thus better understand surface processes and polygenetic topographic evolution. While many Earth scientists have embraced GIT and use GISs, an urgent need exists for more Earth scientists to better understand GIScience. GIScience not only serves as a foundation for development of new technology and technology transfer, it also potentially enables scientific formalizations through computer-based research to produce new geomorphic knowledge and better understandings of the geodynamics of mountains. Similarly, there is need for information scientists to address conceptual and technical issues related to space-time representation, ontology and evolution of landforms, data modeling, operational scale of surface processes, spatial analysis, and dynamic modeling. Many of these topics are inherently related to process-form relationships, topographic organization, spatial processes, forcing functions, and geodynamics.

Unfortunately, so much emphasis on the "technology of GIS" has occurred that some Earth scientists view GIS only as a tool, although a functional continuum exists that ranges from tool to science (Wright et al., 1997). Goodchild (1992) first recognized GIScience as a multidisciplinary field that is concerned with philosophical, cognitive, and scientific treatments of spatial theory, concepts, and methods, including space-time representation, topological relationships, spatial variation, spatial interactions, spatial processes, space-time dynamics, geostatistics, geocomputation, and many other topics. It also represents out of necessity the integration of GIT and applications of GIScience and GIT. The title of this book reflects this inclusive treatment. We suspect, as do many others actively engaged in studying GIScience and geocomputation topics, that the evolution of GIScience may increasingly de-emphasize the focus on technology and emphasize, instead, knowledge and understanding, process over form, dynamics over static representations, and interaction and emergent, entity and system behavior. It is our belief that the linking of concepts and principles in GIScience and geomorphology, and their formal scientific treatments, not the perspective of GIS as a tool, can produce new insights and understandings in both fields.

From a geoscience perspective the misleading and qualitative, Davisian-based study of landforms in the early 20th century was followed in the latter half of the century by the process mechanics perspective, but these studies did not effectively connect process and form, or adequately explain landform evolution. In addition, various *n*-dimensional geomorphometric parameters (Thorn, 1988) of landscape characteristics (i.e., hypsometry, slope, relief) were also used to enable more rigorous quantitative assessments of landforms. With the advent of DEMs, geostatistics, and GIT near the end of the last century, the means for more comprehensive terrain analysis became possible. For example, geostatistics are increasingly being used to characterize topography, using concepts of self-similarity and self-affinity (Rodriguez-Iturbe and Rinaldo, 1997). Fractal concepts enable us to examine different aspects of scale-dependent spatial variation on the landscape and attempt to link it with total energy expenditure, surface processes, geomorphic events, and random chance. Examination of the morphology of mountain landscape systems in the search for process-based explanations of spatial variation can also address controls caused by underlying geologic structures, the presence of geomorphic signatures of varying climates, the coupling of different erosional processes, and the concepts of self-organization that play a key role in the basic general mechanisms that govern landscape evolution.

The goal of development of analytical process-based models that describe complex landform assemblages has been commonly confounded by the admittedly difficult necessity of identifying situations where landforms are truly in equilibrium with prevailing processes. Numerical modeling of processes in mountains now offers the useful option of minimizing the bewildering complexities of the real world and replacing them with the simplicity of abstraction. The iterative combinations of numerically precise tectonic and geomorphic rule sets and equations, coupled with climate modeling and with ever-increasingly sophisticated space-time representations and spatial-modeling capabilities, are leading to many new understandings.

Recent recognition that the shaping of mountains can depend as much on the destructive forces of erosion as on the constructive powers of tectonics (Pinter and Brandon, 1997; Zeitler et al., 2001a, b) is also leading to many new approaches in the study of mountains. Many of the intricate linkages and feedbacks between tectonics, isostasy, climate, and erosional processes have been recognized in that orogeny leads to orography, or the perturbation of the regional climate by topography. Erosion in active orogenic settings is enhanced through greater precipitation on the windward side, thus drawing replacement rock to the surface. Conversely, where climate leads to orogeny the lack of erosion or deposition in extremely arid zones can starve subduction, which in turn can increase friction there and cause greater orogenic uplift, as in the Andes (Lamb and Davis, 2003). New geomorphometric assessments and coupled numerical modeling of such environments are increasingly productive exercises (Burbank and Anderson, 2001).

This book is the result of our experience in integrating GIScience and geomorphology for studying lithospheric processes in a complex mountain system. Our involvement in the international Nanga Parbat Project was to study erosion and complex feedback mechanisms between tectonic, climate, and surface processes responsible for the topographic evolution of the Nanga Parbat Massif in northern Pakistan (Bishop et al., 1998; Bishop and Shroder, 2000; Shroder and Bishop, 2000). To do this work effectively, it was necessary to formalize and implement numerous spatial concepts and theories to account for the scale dependencies of landforms, surface processes and erosion, polygenetic landform evolution, and the coupling of internal and external forcings.

Our research indicates that conceptual and formal treatments of GIScience topics, such as space-time representation, scale, spatial topology, data fusion, geocomputation and landscape spatial organization, can provide new insights into understanding the role of surface processes in mountain topographic evolution. Furthermore, many geomorphology problems can serve as a basis for new directions and developments in GIScience, such as addressing various aspects of scale, gradation and indeterminate boundaries, remote sensing and GIS data and information fusion, and dynamic modeling. Consequently, this book, *GIScience and Mountain Geomorphology*, is an attempt to link knowledge, concepts, and technology so that students and researchers may receive new insights for making further progress in their respective disciplines.

As is usually the case with an emerging field, not everyone is familiar with the body of GIScience knowledge or the capabilities and limitations of GIT. Furthermore, the multidisciplinary integration of knowledge from disciplines is a challenge in its own right, given the amount of material and reductionistic thinking. Therefore, our objectives are to address some of the latest ideas and developments in GIScience and mountain geomorphology, provide some technology solutions for scientific inquiry and monitoring of mountains, and hopefully provide some new insights and research directions on the basis of linking concepts in both fields. It is clear from our experience that not everyone agrees on selected issues, because different perspectives exist.

In our attempt to accomplish these objectives we have organized the book into three sections. Introductory chapters address the linking of concepts and principles related to GIScience and mountain geomorphic systems. A select number of fundamental topics in GIScience are then covered, including the nature of topography and data modeling, terrain analysis and geomorphometry, remote-sensing science and technology, artificial intelligence, spatial analysis and modeling, and scientific visualization. Mountain geomorphology applications of GIScience and GIT include investigations of geoecology, natural hazards, surface hydrology, glaciology, climatology, tectonic and landscape evolution. Each chapter received three or four reviews.

The book has been designed to be of value to upper-level undergraduate and graduate students who must increasingly be familiar with GIScience, GIT and geomorphology for problem solving. The book should also be of value to researchers interested in mountain geomorphology, as we attempt to provide a treatment of how GIS is currently being used. We recognize the challenge of effectively integrating a substantial amount of material and hope to provide the reader with a sense of how the integration of GIScience and geomorphology can lead to better understandings of surface processes and mountain system response. It is not our objective to provide comprehensive treatments of GIScience or mountain geomorphology, as numerous topics in both are not included. Rather, we hope to demonstrate the potential synergy resulting from a multidisciplinary approach.

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April 2003

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Foreword (GIScience perspective)

Geographic information science (GIScience) studies the fundamental principles underlying geographic information systems (GISs). Because GISs can be defined as computer systems for doing just about anything with geographic information, from acquisition and compilation to storage, transformation, analysis, display, and dissemination, it follows that GIScience studies the fundamental properties of a particular class of information and forms an increasingly important subset of information science. GIScience was born about a dozen years ago, when it became increasingly apparent that the enthusiasm for GIS needed to be underpinned by a reflective, scientific research community dedicated to the fundamentals of GIS. These fundamentals include issues of representation, uncertainty, scale, visualization, and at a less technical level, the impacts that GIS has on society, and society's reactions to it.

Techniques for the accurate representation of complex, rugged terrain date only from the 18th century, when the first contour maps were produced. As with many innovations in geographic information technology (GIT), this one was driven in part by the need for accurate targeting of artillery and a better understanding of ballistics. The canal-building mania of the late 18th century was also partly responsible. Contours or isolines proved to be the visual display method of choice, commonly enhanced by hachuring or shading to give a more realistic effect, but not greater accuracy. Surveying techniques based on leveling emerged that were specifically adapted to this display method. By the 1950s, however, the limitations of contours were becoming apparent, particularly the sharp variation in density of information, which is very high along any contour, but virtually absent between contours. The computer visualization technologies that became available in the 1970s, together with the demands of a new generation of missiles, such as the cruise missile, that could navigate by matching the terrain below them to accurate digital representations, led to a rapid proliferation of representation methods: the digital elevation model (DEM); a regular raster of spot heights; the triangulated irregular network (TIN); a mesh of irregular tilted triangles; and many more.

The rapid advances that have been made in terrain representation now underpin a host of GIS applications in rugged environments, particularly mountains. Researchers are asking much more sophisticated and interesting questions: what are the fundamental spatial components of landscape, and can we develop automated methods for extracting them; what new methods such as interferometric radar can be used to produce cheap, accurate representations; what is the relationship between a representation and the processes that modify terrain, and what representations are most useful for understanding processes?

This book is a very timely and welcome contribution to this rapidly developing field. Unlike other books that have chosen to concentrate exclusively on representation, this one places the GIScience issues firmly within the geomorphological and environmental contexts, allowing links to be drawn and relationships evaluated. Thus the individual chapters range in content from a focus on the representational or ontological issues, to a focus on the use of GIS to enlarge our understanding of mountain environments. It provides an excellent illustration of the dual interpretations of GIScience that have emerged in the past decade: the study of the fundamental principles of geographic information and the use of GIS to advance scientific understanding.

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April 2003

Foreword (geomorphology perspective)

Mountains are fascinating places for geomorphologists, some of whom will be rather dismayed by the vagueness of the term, as revealed by spatial ontological issues. With steep surface gradients, and rapid spatial and temporal changes in biophysical variables that control geomorphic processes, mountains provide a range of opportunities to examine geomorphic processes and the unique suite of landforms that they produce. Furthermore, mountains and mountain ranges hold special appeal to geomorphologists and have played a disproportionately large role in the history of the discipline, considering their relative spatial extent.

As documented in *GIScience and Mountain Geomorphology*, geomorphologists are interested in a wide range of mountain processes and forms, ranging from the origin of mega and macro-relief over geologic timescales, through meso to pico-scale forms and processes, to the interactions of surface processes with people, other parts of the biosphere, and global and regional climates. The International Year of Mountains in 2002 increased awareness of initiatives to protect mountain ecosystems and to encourage sustainable development to support mountain people, reinforcing and reinvigorating the interest of geomorphologists in the applied aspects of their work that relate to ecosystem diversity, sustainability, and geomorphic hazards.

One of the challenges, and perhaps one of the appeals of geomorphic research in mountainous areas, has been the relative difficulty of access to field sites. The "good-old-days" of geomorphic research, involving exploration, limited point observations, and a mix of qualitative and quantitative descriptions, resulted in a range of analysis and interpretation approaches. The use of Earth-observing sensors is having a profound influence on the discipline by replacing point data with synoptic coverage, such that new GIS-based analyses and modeling approaches can be used to produce thematic information and quantitative estimates of landscape conditions. Spatial data and geographic information technology (GIT) now provide better access to information about mountain environments and provide the potential for geomorphologists to address difficult scale-related issues for developing new understandings of process-form relationships, internal and external forcings, and feedback and response mechanisms.

A key step in realizing the potential offered by GIScience and GIT is information extraction from integrated spatial data sets. Extracting quantitative and qualitative information about geomorphic features and control variables for geomorphic processes from spectral reflectance characteristics, terrain morphometry, and space-time topological relationships is a major challenge; yet geomorphologists require information products that include such parameters as landforms, erosion, vegetation, snow characteristics, topography, and soil and rock properties. This is especially important in work on natural hazards wherein vulnerability and risk have direct and severe impact on mountain people. As made clear in several chapters in this book, extracting accurate information from remotely sensed data and GIS databases for mountain applications is a nontrivial challenge that requires the combined knowledge and skills of information scientists and geomorphologists.

Rapid advances in data collection technology, such as remote sensor networks, LIDAR (light detection and ranging) systems, and field-based GPS (global positioning system) acquisition methods provide new opportunities and challenges. GIS technology and new methods, are required to address data volume, integration and representation issues, while other methods, such as artificial intelligence, can facilitate information extraction and modeling efforts. New approaches also include geostatistics and temporal analysis to evaluate scale dependencies of surface processes and landform distribution. Furthermore, new forms of scientific visualization can help provide new understandings of patterns in complex datasets and greatly assist planners and managers to use GIS technology and information for decision support. Coupling GIS databases with dynamic process-based models, such as global and regional climate models or ice sheet basal boundary conditions, not only provides new modeling opportunities and evaluation of feedbacks, but also requires new ways to automate up- and down-scaling for model parameterization. Furthermore, developments in GIScience can potentially lead to new parameterization schemes that explicitly account for scale dependence. Automation will be required to effectively address the sheer mass of data. Automation will, however, introduce new issues, as assumptions are made which can effectively result in misinterpretation. Geomorphologists must be aware of the assumptions and the mathematical and computational underpinnings of algorithms and methods. This goes beyond the fundamental principles of utilizing a GIS (e.g., data input, management, manipulation, analysis, and output).

Geomorphologists are more aware of mapping approaches, but are less familiar with GIScience and many of the cutting-edge technologies and issues associated with space-time analysis. Some geomorphologists still view GIS as simply mapping or visualization software, rather than a powerful new analytical tool. This book, *GIScience and Mountain Geomorphology*, provides understandable introductions, overviews, and discussions framed in the context of mountain geomorphology issues. Thus it is a useful and unique resource for mountain geomorphologists. At the same time, many of those developing the technologies and analysis capabilities can benefit from examining the issues and objectives in mountain geomorphology, for they can be used to help address and formalize selected GIScience issues. Rich interchange between geomorphologists and information scientists, mediated by those with interests in both fields, as represented in this book, is the way to make good progress.

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Foreword (environmental/geographic perspective)

No region of the world creates more excitement and awe than mountains. Their beauty, perceived remoteness, and inaccessibility only further enhance their mystique. Because of their mystery and striking appearance, we all seem to want to know more about them, about their peoples and their environments, as well as increasing our scientific knowledge of mountain processes. In short, we want to understand Mountain Geography. Mountain Geography encompasses all things in the people–environment continuum. *GIScience and Mountain Geomorphology* goes well beyond its title, integrating as it does the studies of climate, ecology, geology, geomorphology, hydrology, and natural hazards (i.e., geography and environment are integrated through one of our most powerful research and analytical tools—GISs).

Indeed, this book encompasses a very important and large portion of Mountain Geography; when one considers the complexity and importance of some of the topics within—for example, the global climatic impact of mountain barriers, or the importance of slope and avalanche stability to the livelihoods of up to one-quarter of the Earth's populace, or that mountains supply about one-third of global surface water, or the dynamics of treeline—then understanding mountain environments in an integrated fashion becomes ever-more important. GIScience allows researchers, analysts, and policy makers to see and therefore to understand multiple aspects of mountain environments at once. *GIScience and Mountain Geomorphology* brings the study of mountain environments and technology together in such a way that it should prove useful to scholars, students, and decision makers alike.

The editors and contributors to this volume have done an excellent job in providing a state-of-the-science volume that clearly shows how GIScience has and will continue to greatly enhance our understanding of mountain environments. The focus of the research within is spatial and temporal understanding, thus bringing science back to its geographic roots where including and understanding the spatial dynamics of natural phenomena and human activity are more than just a fad; it is inherent in what geographers, other scientists, and decision makers must do to more fully understand our environment. The advent of GIScience and GITs has allowed us to integrate landscape evolution, process geomorphology, environmental analyses, and human impacts in ways such that we are only now starting to truly understand how mountain systems operate. This text brings us to that cutting edge.

In addition to this book being an important scientific contribution, it was begun as a contribution to the United Nations International Year of Mountains (IYM)—2002. I am proud that the editors and contributors are from the broad geographic and geoscience communities. Several organizations representing those communities recognize this as well and have kindly lent their "sponsorship" to this scholarly undertaking. The Mountain Geography Specialty Group of the Association of American Geographers, the International Geographical Union Commission on Diversity in Mountain Systems and the Mountain Institute all find this volume worthy of their support. The United Nations Food and Agriculture Organization, the body charged with implementing IYM, also recognizes that the book supports IYM objectives and as such has honored the editors with a stamp of IYM approval ... strong support for a job well done!

Donald A. Friend
Founder, Mountain Geography Specialty Group of the Association of American Geographers
Member, International Geographical Union Commission on Diversity in Mountain Systems
April 2003

Glossary

aiguille	sharp, jagged rock spires formed by intense frost shattering.
albedo	ratio of light reflected by a planet to that received by it.
arête	knife-edged ridge caused by glacial erosion.
bergschrund	uppermost crevasse of a glacier where it pulls away from the bedrock.
bornhardt	a large, upstanding rounded inselberg or "sugarloaf" of smooth bedrock.
corestone	spheroidally weathered boulder of residual bedrock.
exitance	energy departing the Sun
facies	sum total of all the effects of the environment of deposition on a resulting sediment deposit.
Forbes bands	transverse light and dark bands in a glacier.
Fourier series	infinite series that involves linear combinations of sines and cosines and approximates a given function on a specified domain.
gelifraction	frost shattering of rock and sediment.
gendarme	isolated, upstanding pinnacle of rock or sediment isolated by erosion around it.
grusification	granular disintegration of bedrock formed through decomposition of intervening minerals leaving a pebbly grus of residual mineral pieces.