3.1 Remote Sensing and GIScience in Geomorphology: Introduction and Overview

MP Bishop, Texas A&M University, College Station, TX, USA

Glossary

Digital elevation model A digital elevation model (DEM) is generally a land-surface model that attempts to accurately portray the altitude field of the topography. In geomorphology, it commonly takes the form of a raster data layer representing a field of square tessellations. The grid cell resolution is based upon the source data and the desired scale for representing the topography.

Digital terrain modeling Digital terrain modeling (DTM) refers to a workflow process of acquiring data that samples the altitude field, preprocessing the data to generate a digital elevation model, and error and uncertainty analysis to identify and remove systematic and random errors.

Geographic information science Geographic information science (GIScience) is an emerging multidisciplinary field that attempts to understand the nature of spatio-temporal information, with a focus on geographic representation, spatial analysis and modeling, and addressing scientific problems. It represents a body of geographical and technical knowledge concerned with philosophical, cognitive, and scientific treatments of spatio-temporal theory and concepts. GIScience is often used as an umbrella term to refer to developments in a variety of fields that have contributed theory, concepts, and new information technology. It also refers to those disciplines involved in the investigation of the utility of information technology for applied information production and problem solving.

Geographic information systems A geographic information system (GIS) is a software system that can be used to store, manage, manipulate, analyze, and display spatially referenced data. It can also be thought of as a decision support system, as spatial data are analyzed to produce information that is used to support management and planning decisions.

Geomorphological mapping Geomorphological mapping is a general term that refers to mapping various aspects of the geomorphological system. This can include numerous themes such as land systems, hydrology, surface material and structure, morphometry, sediment transfer, surface-process regimes, and chronology.

Bishop, M.P., 2013. Remote sensing and GIScience in geomorphology: introduction and overview. In: Shroder, J. (Editor in Chief), Bishop, M.P. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 3, Remote Sensing and GIScience in Geomorphology, pp. 1–24.

Geomorphometry The discipline that is concerned with the science of quantitative land-surface characterization.

Imaging spectroscopy Imaging spectroscopy refers to the collection of surface spectra from a spectrally contiguous region of the electromagnetic spectrum that includes the visible, near-infrared, and short-wave infrared regions of the electromagnetic spectrum. The spectra are collected using a very narrow spectral interval (8–12 nm) and hundreds of images are usually acquired. This allows detailed biophysical assessment and mapping of the Earth surface. Imaging spectroscopy is also commonly called imaging spectrometry or hyperspectral remote sensing, as the dimensionality of spectral data (images) is very high. The accuracy of the surface spectra for each pixel is dependent on the spatial, spectral, and radiometric characteristics of the sensor.

Land-surface objects Land-surface objects are spatial entities that represent a meaningful segmentation of the Earth's surface. They are generated from land-surface parameters using a variety of algorithms and methods, and generally relate to the morphology of the topography in terms of landform elements, features, or functional units. Terrain segmentation can also relate to topographic position and structure, surface material, or process domains, if properly defined and delineated.

Land-surface parameters Land-surface parameters are also called geomorphometric parameters, and they attempt to quantitatively characterize various aspects of the topography. They can be defined and classified based on geometry, scale, and by surface-process characterization. They are used to generate land-surface objects and characterize process mechanics in surface-process modeling. A variety of parameters such as slope, slope azimuth, curvature, surface roughness, and relief are used for studying geomorphological systems and for geomorphological mapping.

Light detection and ranging Light detection and ranging (LiDAR) is a form of active remote sensing that is based on laser-light technology to obtain information about the Earth surface. LiDAR data can be used to produce high-resolution digital elevation models that attempt to characterize a surface or a bare-earth representation of the topography.

Near infrared The near-infrared (NIR) represents a region of the electromagnetic spectrum that ranges from 0.7 to 1.3 μm. Optical sensors record NIR light reflected from the surface. NIR imagery can be used to assess and map vegetation, water, and other environmental characteristics.

Object-oriented analysis Object-oriented analysis refers to the analysis of surface objects to determine their inherent properties. Terrain or image segmentation is first required to group tessellations into meaningful spatial entities that represent land-cover or terrain features. Spatial analysis is required to isolate surface objects at a variety of scales. Object-oriented analysis is then used to characterize object properties such as size, shape, and topographic conditions. Spatial analysis of objects can then provide detailed information about the context and topological relationships among surface objects. This analysis has been found to be superior to pixel-based methods for mapping a variety of Earth-surface features.

Short-wave infrared The short-wave infrared (SWIR) represents a region of the electromagnetic spectrum that ranges from 1.3 to 3.0 μm. Optical sensors record SWIR light reflected from the surface. SWIR imagery is routinely used for snow and ice, mineralogical, and lithological mapping.

Spatial hydrology Spatial hydrology refers to the linking of remote sensing and GIS with hydrological modeling efforts. Numerous levels of coupling of GIScience and hydrology exist, although a major focus has been on using various forms of data and methods to estimate key hydrological parameters that drive hydrological models.

Spectral absorption feature A spectral absorption feature is a wavelength-dependent feature of a spectral reflectance curve. It is characterized by a localized decrease in reflectance due to the absorption of energy by surface matter, given its composition and chemistry. The prominence of the absorption feature is determined by its depth, width, and shape. A spectral curve can exhibit numerous spectral absorption features depending on sensor-system characteristics and surface compositional variations. Many surface materials such as biochemicals or minerals have diagnostic absorption features that can be used to assess surface biophysical characteristics. Imaging spectroscopy makes use of spectral absorption features to assess and map biophysical conditions on the Earth's surface.

Thermal infrared The thermal infrared (TIR) represents a region of the electromagnetic spectrum that effectively ranges from 3.0 to 15 μm. This region of the spectrum is used to assess the thermal properties of the landscape and emission is related to surface temperature. Thermal imagery is used in a variety of disciplines including geomorphology, volcanology, glaciology, and for mineralogical/lithological mapping.

Abstract

Geospatial technologies are having a profound effect on geomorphology. Remote sensing and geographic information system studies are now commonplace in Earth science investigations. Significant advances have occurred in sensors, geodesy, photogrammetry, geophysics, computer science, statistics, and pattern recognition. Consequently, it is now possible to quantify landscape morphology, investigate climate forcing, link process with patterns and form, and enhance our understanding of scale dependence and the polygenetic nature of landscape evolution. This chapter introduces current capabilities and new developments that are relevant to geomorphological investigations. The emphasis is on using data and new analysis approaches to better understand geomorphological systems and landforms.

3.1.1 Introduction

Earth science investigations are increasingly utilizing geospatial technologies (Bishop and Shroder, 2004b; Hengl and Reuter, 2009; Bishop et al., 2012). The rapid proliferation of geospatial technologies is related to advances in geodesy, photogrammetry, geophysics, computer science, statistics, remote sensing, geographic information technology (GIT), and numerical modeling, which have collectively revolutionized the field of geomorphology (Bishop et al., 2001; Shroder and Bishop, 2003; Bishop and Shroder, 2004a;). Scientists are routinely utilizing new spatio-temporal data, geocomputational algorithms, and processing approaches and models, which now allow assessments far beyond traditional geomorphological mapping. It is now possible to quantify landscape morphology (Pike, 2000; Hengl and Reuter, 2009), assess surface biophysical conditions (Florinsky, 1998; Liang, 2007; Smith and Pain, 2009; Tarolli et al., 2009), assess near-surface conditions, link process with form and patterns (Allen and Walsh, 1993; Montgomery et al., 2004), and improve our understanding of scale dependence and the polygenetic nature of landscape evolution (Walsh et al., 1997; Tate and Wood, 2001; Bishop et al., 2003). Nevertheless, such rapid utilization of information technologies must be carefully examined, given the empirical nature of utilizing geographic information systems (GIS), the need for formalization to address numerous issues, and requirements of accuracy and repeatability (Bishop et al., 2012).

Numerous conceptual/theoretical and methodological issues are at the heart of effectively utilizing spatio-temporal data and GIT to study geomorphological systems (Bishop et al., 2012). Therefore, Earth scientists need to be fully aware of current capabilities as well as the issues and challenges related to geomorphology and geographic information science (GIScience) (Bishop and Shroder, 2004b; Bishop et al., 2012). Geospatial technologies can be used to address various conceptual and practical issues such as heterogeneous surface composition with fuzzy-classification membership (Warner and Shank, 1997), indeterminant boundaries and features (Burrough, 1989; Usery, 1996; Burrough et al., 2000; Smith et al., 2000; Deng and Wilson, 2008), hierarchical organization and spatial analysis using object-oriented technology (Ralston, 1994; Brändli, 1996; Schmidt and Dikau, 1999), scale dependence of properties and patterns using geostatistics (Tate and Wood, 2001), and objective mapping using different analytical approaches (e.g., descriptive statistics, inferential statistics, artificial intelligence, and various analytical reasoning technologies).

Nevertheless, numerous limitations are associated with the use of existing cartographic representations of environmental and geomorphological information, as parameterization schemes that uniquely characterize the formal structure of natural systems and information associations (i.e., attributes, space, and time), and the formal linkage of multiple processes and forms in space–time is not readily available. Consequently, cartographic representational schemes are still effectively being used, although more complex representational schemes typically occur outside of GIS environments. Addressing numerous science issues will most likely require multidisciplinary collaboration between Earth and information scientists (Bishop and Shroder, 2004b).

From a more methodological perspective, advances in the development and deployment of new sensors and mobile platforms will provide for new forms of data across a multitude of scales. This has enabled researchers to address numerous issues at the requisite scale. Active research areas include the assessment of surface processes and their impact on erosion and landscape evolution (e.g., Finlayson et al., 2002; Finlayson and Montgomery, 2003) and the evaluation of data and methods for geomorphological mapping (e.g., Saadat et al., 2008; Schneevoigt et al., 2008). The role of remote sensing in generating high-quality digital elevation model (DEMs) is essential (Wilson and Gallant, 2000), as the topography inherently incorporates a multitude of morphologies that are generated due to the interaction of climate, tectonic, and surface processes. The development and evaluation of new techniques and analytical approaches for information extraction from multispectral, multitemporal, and DEMs is an active research area (Bishop and Shroder, 2004b; Bishop et al., 2012). Investigators have focused on the technical aspects of developing GIS databases (Gustavsson et al., 2008), developing geomorphometric mapping software (Klingseisen et al., 2008), mapping specific landform features, and developing new ways to visualize geomorphological information (Vitek et al., 2008). A plethora of quantitative metrics and approaches exist. The advantages and limitations, however, of numerous algorithms and multistage processing approaches have not been rigorously evaluated and compared for specific applications. Furthermore, standardized formalizations for specific applications are urgently needed. Consequently, numerous issues related to taxonomy, scale, process mechanics, feedback mechanisms, system dynamics and states, representational schemes, algorithms and processing protocols, visualization of complex information, and effective information distribution need to be accounted for.

The objective of this chapter is to place the current volume into perspective and provide an overview of remote sensing and GIScience contributions to geomorphology and the Earth sciences in general. It is important that significant capabilities be highlighted so that scientific inquiry may be facilitated by the use of spatio-temporal data and GIT. It is also necessary to highlight the challenges and issues associated with the use and evolution of GIT, so that rapidly evolving capabilities effectively address scientific and practical issues. Given the exceptionally diverse fields of study that encompass Earth science and GIScience, it is not possible to cover all developments in a comprehensive fashion. Rather, the topics that have the most direct significance for understanding geomorphological systems and landforms have been selected.

3.1.2 Geospatial Technology and Fieldwork

Fieldwork has been and will continue to be an important aspect of scientific inquiry and mapping. The nature of field equipment has radically changed from analog to digital devices, and automated sensors and systems ensure specific levels of accuracy (e.g., location, spectra-based mineral identification, microclimate). Field sensors can be used for recording many different landscape parameters related to microclimate, ecological, hydrological, sedimentological, and lithological systems. Telecommunications and computers allow the rapid collection and analysis, whereas mobile sensor platforms allow expanded coverage.

Relatively new quantitative spatio-temporal data are related to advances in geodesy. A significant milestone was the development of the global positioning system (GPS). A constellation of GPS satellites communicate their position with each other and ground receivers, such that attribute information collected in the field is tagged with precise spatio-temporal coordinates. Spatial and temporal information can be used to compute distances, directions, and rates of change. Consequently, GPS technology is routinely used in fieldwork, and GPS data have significantly contributed to the understanding of environmental change, glaciation and glacierization, tectonics, and facilitate soils and landform mapping (e.g., Bilham et al., 1997; Gao and Liu, 2001; Banerjee and Bürgmann, 2002; Sella et al., 2007; Bishop et al., 2010; Flowers et al., 2011).

Similarly, advances in laser, computer, and communication technology have resulted in new surveying equipment. Field devices include laser-based total stations, laser rangefinders, hand-held spectral radiometers, radiation sensors, and many other portable sensors that transfer data to loggers or satellites for subsequent downloading. Interactive data loggers can be used to visually examine digital aerial photography or satellite imagery in the field, and GIS data layers can also be viewed to facilitate fieldwork. This allows improved data collection for geomorphological mapping, sampling, and targeted investigations.

Terrestrial laser scanners can now be used to study surface processes in great detail. These laser-scanning devices can be mounted on tripods, jeeps, or terrain rovers to collect high-resolution 3-D point clouds (Figure 1). High-resolution DEMs can be generated over relatively short time intervals. Rates of erosion, deposition, and ablation can be estimated by comparing altitude values over time. Furthermore, process mechanics can be studied, as the relationships between process, form and topographic evolution can be quantitatively characterized.

New developments in field-based radiation sensors also facilitate field and remote sensing studies of geomorphological systems. Investigators can use field-based spectral radiometers and spectra-based mineralogical identification systems to collect spectra in the field and identify the mineralogical composition of rocks, sediments, and soils. Specific biophysical characteristics of surface materials include primary silicate minerals, secondary silicate minerals, water content, and organic matter. Furthermore, samples of material collected in the field can be brought back to the laboratory for subsequent spectral analysis.

Other radiation sensors are used to measure the magnitude of incoming and outgoing radiation that governs many surface processes and the surface-energy budget. Consequently, pyranometers, pyrheliometers, albedometers, and shortwave and longwave net radiometers are used to measure various components of the radiation-transfer cascade. Microclimatic conditions influence weathering, ablation and melt water production, glacier erosion, avalanching, and other mass movement processes. Such field-based investigations are critical for evaluating the information content in multispectral satellite imagery and validating the accuracy of thematic information generated from satellite-derived data and numerical models. Such validations (e.g., surface temperature and albedo estimates from imagery) provide new opportunities for geomorphological assessment via remote sensing.

Figure 1 Terrestrial laser scanning at the Chalk Cliffs Natural Debris Flow Laboratory (Summer 2010). A Leica HDS C10 laser scanner was used for repeat surveying. Pictured in the image are Thad Wasklewicz (yellow helmet) and Dennis Staley (red helmet). Photograph courtesy of Thad Wasklewicz, East Carolina University.

Given the increasing miniaturization of sensors and near-field communication capabilities, investigators are recognizing the potential of establishing field-site sensor networks to characterize and monitor changes on the landscape. The parameter list for such networks is ever increasing and potentially includes atmospheric variables, photography, and surface parameters. Depending on the spatial density of station sensors, data can be transmitted to satellites and downloaded to produce spatio-temporal information layers via spatial interpolation. Future developments in sensor networks will most likely include robotic rovers, where information collected from the network governs the location of sensors, such that the network adapts to environmental conditions in an attempt to better characterize the spatio-temporal variability of phenomena being collected by the sensor network.

Communication technology now allows ground control of unmanned ground and aerial vehicles, which provides new opportunities for collecting data in the field. The University of Arizona, in a project led by Jeffrey Kargel, and assisted by the Kathmandu-based International Centre for Integrated Mountain Development (ICMOD), has conducted feasibility studies for the use of remotely controlled boats equipped with side scan sonar and other instruments to study glacial lakes (Figure 2). Featured here is a boat deployment on Imja Lake (Imja Glacier in the background), near Mount Everest, Nepal. These studies have investigated lake bathymetry and suspended sediments, and density stratification of the water column. Routine deployments in hazardous or dangerous lakes are the goal of these studies. The potential advantage of boat deployments, as opposed to conventional human-piloted boat deployments, is that the small watercrafts are more readily transported to remote locations and their deployment leaves the scientific crew safely onshore.

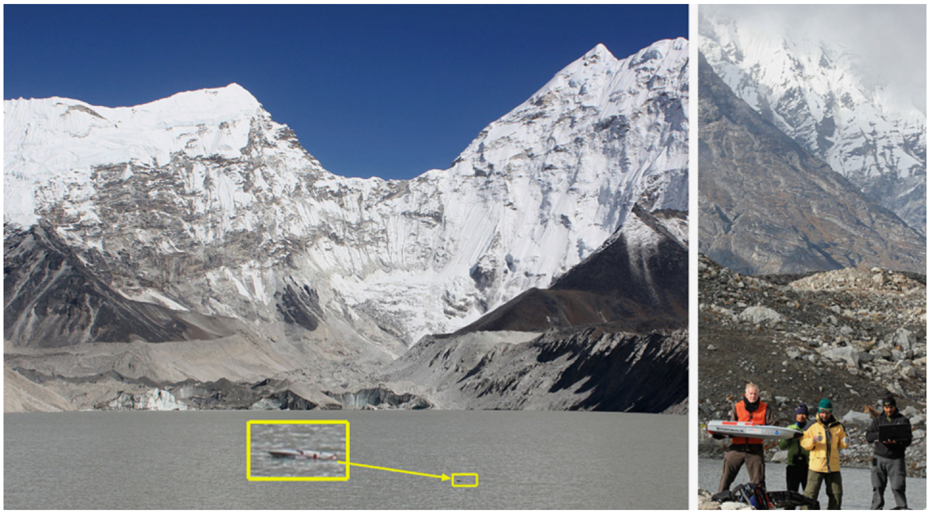

Figure 2 Remote-controlled boat on Imja Lake (Imja Glacier in the background), near Mount Everest, Nepal. The boat has a sensor payload that allows the acquisition of bathymetric information, video, and water temperature. Such mobile platforms and sensors are useful for studying supraglacial lake development and monitoring flood hazards associated with proglacial lakes and landslide-valley impoundments that cause catastrophic flooding. Photography courtesy of Jeffrey Kargel, University of Arizona.

Deployment of terrain rovers with sensors is also being tested at the University of Arizona by Wolfgang Fink. Research is aimed toward the development and deployment of truly autonomous observing systems. These platforms and sensors involve semi-autonomous navigation, where input from scientists would be greatly reduced. Such technology and equipment involves advancements in semi-automated data analysis and autonomous scientific interpretation and decision making using various forms of artificial intelligence. Other possibilities also include aircraft and gliders with various sensor arrays.

Supplementary material related to this article can be found online at doi:10.1016/B978-0-08-088523-0.00040-X.

A host of different geoscience fieldwork applications are also becoming available for field-portable laptop computers, wherein checklists for data collection, section measuring, and other typical field data can be collected electronically. Given many new possibilities, fieldwork is becoming more complex and automated. Special attention must be paid to the choice and suitability of sensors and technologies, sensor-system deployment and sampling, key data parameters, and storage issues. Collectively, geospatial technologies have greatly enhanced fieldwork and data collection.

3.1.3 Remote Sensing and Geomorphology

Advances in optical, microwave, and light detection and ranging (LiDAR) remote sensing now allow a multitude of landscape information to be acquired. Data and information characteristics are closely tied to sensor characteristics that must be carefully considered. Improvements in spatial resolution enable better recognition of small-scale objects. A recent trend is high-resolution imagery which is now available via commercial systems, although cost is an issue for many. Similarly, the evolution of sensors has brought about an increase in spectral resolution that includes measuring more regions of the electromagnetic spectrum with improved spectral bandwidths. Hyperspectral sensors, or imaging spectrometers, record hundreds of spectral images using 8–12 nm bandwidth ranges. Better radiometric resolution (10–12 bits) also allows sensors to be more sensitive to reflectance and emission variations. Microwave remote sensing has also seen significant advancements, and LiDAR remote sensing provides numerous possibilities for the study of the atmosphere and landscape. Consequently, a plethora of spatio-temporal data can be used by Earth scientists.

3.1.3.1 Photography and Videography

Ground photography has historically played a significant role in conducting fieldwork. Pictures of landforms, topography, surface cover, and environmental conditions have been used to document landscape features, and provide the basis for qualitative interpretations of landforms and surface processes. Photography, based on the chemical processing of film, was mainstream for a considerable amount of time. Technological advances have recently resulted in the use of 'digital photography' and fieldwork now involves the use of digital cameras that generate megapixel images (Figure 3). Nevertheless, the ability to acquire repeat ground 'photography' is important in documenting the Earth's surface and for change detection. Classic examples involve monitoring lake water levels, glacier advancement and retreat, soil erosion, vegetation succession, mass movements, and in general, landscape evolution (given sufficient time).

Digital camera technology is rapidly advancing and it will soon be possible to obtain giga-pixel digital images. Research is underway to produce a digital camera that can take panoramic images. A single-shot image of a landscape would allow a detailed examination of the entire landscape, as such high-resolution systems generate detailed data for subareas within the panoramic scene. This technology, coupled with photogrammetry and GPS technology, will markedly improve

Figure 3 Ground 'photograph' of the north-facing Braldu Valley in the central Karakoram Himalaya of Pakistan. Glaciation has had a profound influence on the topographic evolution of the Karakoram, and such data document glacially polished valley walls, high-altitude erosion surfaces, and a variety of depositional features associated with mass movement and catastrophic flooding. Fieldwork and ground photography allow geomorphological mapping and reconstruction of significant erosion events.

our ability to comprehensively document the landscape as never before. Critical issues involving data acquisition include data volume and storage, computer memory, and processor speeds.

Such technology will inevitably be placed on mobile platforms, thereby providing detailed spatial coverage. One may also envision giga-pixel multispectral images. Consequently, these systems would represent state-of-the-art sensors for aerial and space 'photography,' and such systems would provide for a tremendous volume of multitemporal data for change-detection studies.

It should be kept in mind, however, that a tremendous amount of historical aerial and space photography can be used to study geomorphological systems. Classic examples include the use of multitemporal aerial photography for studying coastline changes and sediment transport, aerial and space photography for monitoring glacier fluctuations, space photography and imagery for studying regional geomorphological conditions, and ground and aerial photography for inventory and assessment of mass movements. It is critical to understand that multitemporal 'photography' serves as baseline information on which existing data for quantifying environmental change can be compared.

Developments in videography can also considerably improve our understanding of surface processes and landforms. Ground and aerial video of catastrophic events document such events and provide insights into the nature of process mechanics. Examples include debris flows and landslide events, earthquakes, and associated landscape changes, tsunamies, and flooding events. Thermal videography is also being increasingly utilized in volcanology (e.g., Vaughan et al., 2005), and in many surface applications to study energy budget and depositional processes (e.g., Hardgrove et al., 2009). Many examples are presented in Chapter 3.2 by Shroder, as he specifically addresses the use of photography and videography in geomorphology.

3.1.3.2 Imaging Spectroscopy

Optical imaging sensors record the magnitude of reflected and emitted radiation from planetary surfaces. Sensors can be mounted on aircraft and satellite platforms to obtain multispectral and multitemporal information about surface characteristics. The data are qualitatively and quantitatively analyzed to generate thematic and quantitative biophysical information. The nature and accuracy of remotely derived information is highly dependent on sensor characteristics regarding spatial, spectral, and radiometric sensitivity. Consequently, not all sensors can provide similar information, as they have been specifically designed to address issues related to sensor-system evolution and application objectives.

With the advent of resource satellites, starting in the 1970s and 1980s, Earth scientists were able to assess and map the regional geomorphological conditions on the Earth (e.g., Short and Blair, 1986). Numerous governments subsequently launched their own satellites with different sensor payloads, such that currently, a multitude of information products and satellite data are routinely used in Earth science applications. The evolution of imaging sensors has been one of improving spatial, spectral, and radiometric resolution and signal-to-noise ratio. This evolution has already had a profound influence on Earth science, and high spatial-resolution sensors (1–5 m) allow improved thematic mapping capabilities. Nevertheless, many sensors do not have a comparable spectral resolution, exhibiting a limited number of spectral bands that may or may not cover key regions of the electromagnetic spectrum.

The primary sensor characteristic that governs image information content is spectral resolution. Therefore, more spectral bands theoretically facilitate obtaining unique information. In practice, this is not the case, as the amount of generalization associated with the spectral bandwidth determines the degree of multicollinearity in the data. Imaging spectroscopy represents the collection of many narrow, spectrally contiguous bands, such that each pixel contains a spectrum. In the literature, imaging spectroscopy is also commonly referred to as imaging spectrometry or hyperspectral remote sensing. Imaging spectroscopy has existed for the past three decades, and has witnessed exponential growth recently, as new sensors are being developed and evaluated, and hyperspectral data are being increasingly utilized in a large variety of domains including ecology, hydrology, soil science, geology, and geomorphology (Schaepman et al., 2009).

3.1.3.2.1 Sensor parameters

Electro-optical sensors consist of detectors that record the incident at-sensor radiance as an electronic signal. The signal varies over time, space, wavelength, and amplitude depending on sensor responsivity, which in general is called resolution. The sensor characteristics can significantly alter the signal and ultimately determine the level of generalization and the nature of the information represented in the imagery. Furthermore, knowledge of sensor characteristics is required for interpretation and analysis, given sensor influence on spectral variability.

The spatial resolution of a sensor is usually referred to as the ground instantaneous field-of-view (GIFOV). It is the geometric projection of the detector width, w, and is defined as

$$\mathrm{GIFOV} = 2.0H\tan\left(\frac{\mathrm{IFOV}}{2.0}\right) = w\frac{H}{f}, \quad [1]$$

where IFOV is the instantaneous field-of-view, H is the height of the sensor above the Earth surface, and f is the focal length of the sensor. The GIFOV determines whether an object will be resolved by the system, as GIFOV and object dimensions determine the sensor's object-discrimination capabilities. The sensor-system averages the recorded signal over the spatial extent of a pixel. Specifically, the spatial response of a sensor is characterized by the optical point-spread function (PSF). It is a weighting function that spatially distorts the inherent spatial geometry at the surface of the Earth. A common model for the PSF is the 2-D Gaussian function such that

$$\mathrm{PSF}(x,y) = \frac{1.0}{2.0\pi ab}\exp(-x^2/2a^2)\exp(-y^2/2b^2), \quad [2]$$

where a and b determine the width of the PSF in the cross- and in-track directions. For well-designed optics, $a=b$. Consequently, moderate- to coarse-resolution sensors produce spectral data that are not representative of a single type of matter or biophysical property, and the system produces composite spectra.

The spectral resolution of the sensor is also an important consideration, as sensors exhibit spectral bands that measure energy in different regions of the spectrum. In theory, different regions of the spectrum can be used to obtain different information, as matter/energy interactions can be fundamentally different. Consequently, it is advantageous to sample the visible (0.4–0.7 μm), near-infrared (0.7–1.3 μm), shortwave infrared (SWIR) (1.3–3.0 μm), and thermal (3.0–100 μm) regions of the spectrum. The total amount of energy measured in each spectral band must be averaged over a spectral bandwidth, and each detector has a spectral-response function (SRF) that characterizes the wavelength weighting. An ideal SRF is modeled as a Gaussian function such that

$$W(\lambda) = \exp\left[\frac{(\lambda - \lambda_c)^2}{2\sigma^2}\right], \quad [3]$$

where λ_c is the wavelength corresponding to the peak weighting and $\sigma = \mathrm{FWHM}(8\log(2))^{-0.5}$. The full-width at half-maximum (FWHM) effectively represents the spectral bandwidth, although technically this represents the width where W is 0.5. A wider spectral bandwidth results in more spectral generalization. The central wavelength peak and bandwidth determine whether spectral absorption features will be characterized in recorded spectra. The spectral averaging can be represented as

$$\overline{L}(\lambda) = \frac{\sum_{\lambda_1}^{\lambda_2} W(\lambda)L(\lambda)}{\sum_{\lambda_1}^{\lambda_2} W(\lambda)}, \quad [4]$$

where $\overline{L}$ represents the average radiance value and L represents the radiance recorded by the sensor.

In practice, sensor selection is an important aspect of remote sensing, as resolution characteristics determine applicability for problem solving. For example, some panchromatic sensors may have a higher spatial resolution, although the data are not useful for biophysical applications, given the SRF (**Figure 4**). Other sensors provide more detailed spectral information with less spectral generalization (**Figure 5**). Finally, imaging spectroscopy depends on a very fine spectral response, such that there are a large number of spectral bands and narrow spectral bandwidths (**Figure 6**).

The electronic signal must also be amplified to provide for a sufficient signal for quantification. The electronic gain and offset values are set based on an expectation of the range in the magnitude of incident radiance from different environments. The amplified signal is then sampled and quantified into digital number (DN) values. Therefore, a DN value for each pixel is represented as

$$\mathrm{DN}(\lambda) = int[g(\lambda)e_s + o(\lambda)], \quad [5]$$

where e_s is the electronic signal, g is the electronic gain, and o is the electronic offset. The number of discrete DN values that represent the magnitude of radiance defines the radiometric resolution of the sensor. This represents 2^n bits over the dynamic range in radiance. This characterizes the sensitivity of the sensor to record variations in the magnitude of energy reflected from the landscape. Most modern sensor have an 8–12-bit radiometric resolution.

3.1.3.2.2 Reflectance properties and applications

The reflectance properties of surface features are based on their composition and molecular processes. Incident radiation is preferentially absorbed by molecules. The total energy of a molecule is the sum of electronic, vibrational, and rotational energy. Changes in the energy state are governed by electronic and vibrational processes. The absorption of energy results in absorption features in reflectance spectra. Emission of photons results from a transition to a lower energy state. Consequently, reflectance spectra can be used to diagnostically detect the presence of a variety of materials, as many exhibit absorption features and unique spectral reflectance patterns.

Imaging spectroscopy can be used for a variety of geological and soil-science applications. Mineral detection is critical for many applications. Imaging spectroscopy has long been used to explore for mineral deposits and for lithological mapping (Goetz and Rowan, 1981; Kruse et al., 1993). This is possible as electronic transition and charge transfer processes associated with transition metal ions determine the position of diagnostic absorption features in the spectra of minerals (Burns, 1970). Vibrational processes in H_2O and OH^- also produce overtone absorptions. Consequently, the position, shape, depth, width, and asymmetry of absorption features are controlled by the crystal and chemical structure of the mineral (van der Meer and de Jong, 2006). Absorption bands can be found in the visible, NIR, and SWIR regions of the spectrum. For a more detailed characterization of mineral reflectance spectra, see Grove et al. (1992).

The reflectance spectra of minerals are well known, and numerous spectral libraries can be used to facilitate remote-sensing studies. Specifically, the United States Geological

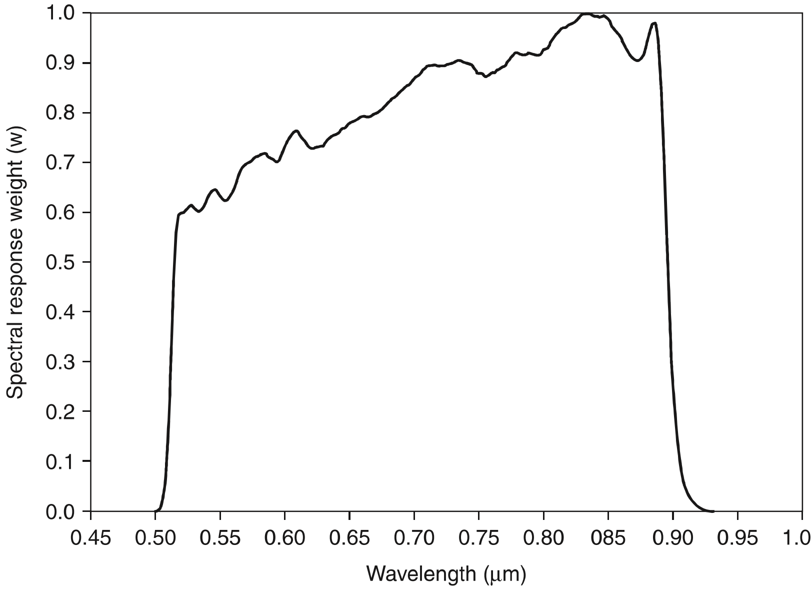

Figure 4 Landsat-7 Panchromatic sensor spectral response function. The sensor is more sensitive to the near-infrared region of the spectrum, and this reduces the atmospheric effects in the imagery. The wide spectral bandwidth does not allow the imagery to be utilized to assess specific biophysical conditions because extensive spectral averaging does not accurately characterize narrow absorption features.

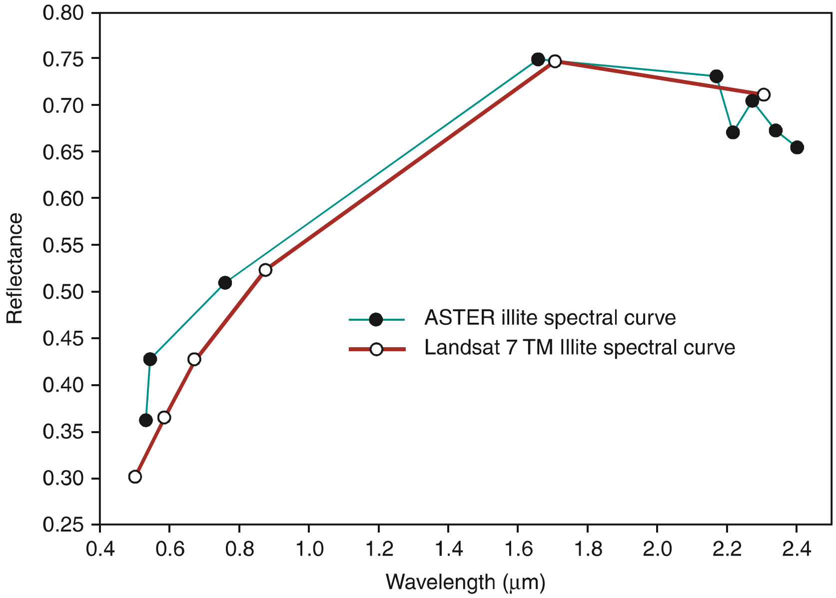

Figure 5 Simulated ASTER and Landsat-7 Thematic Mapper spectral-reflectance curves for the secondary-silicate mineral illite. Sensor spectral-response functions determine the degree of generalization associated with the spectral curve. This example demonstrates that ASTER data depict the illite absorption feature in the SWIR, whereas the TM spectral curve does not. Consequently, spectral resolution must be carefully considered for different applications.

Survey Spectral Library and the ASTER spectral library can be used to simulate composite spectra using spectral mixing models. In addition, spectral matching algorithms can be used to assess the degree of similarity between pixel spectra and laboratory spectra. These types of analyses allow assessment of the potential presence of specific minerals at the surface. Rock spectra can be simulated based on standard or assumed mineralogical composition. Linear and nonlinear spectral mixing models and model inversion can be used for lithological and soils mapping and finding mineral end-member distributions, respectively.

Imaging spectroscopy provides many new capabilities for studying soil properties (Ben-Dor et al., 2009). Soil degradation due to salinity, and caused by rising water tables or irrigation, can be assessed via hyperspectral remote sensing (Taylor et al., 1994; Metternicht and Zinck, 2003). Specifically, Taylor et al. (1994) showed that soil salinity could be mapped using air-borne spectrometer data. More specifically, Taylor (2004)

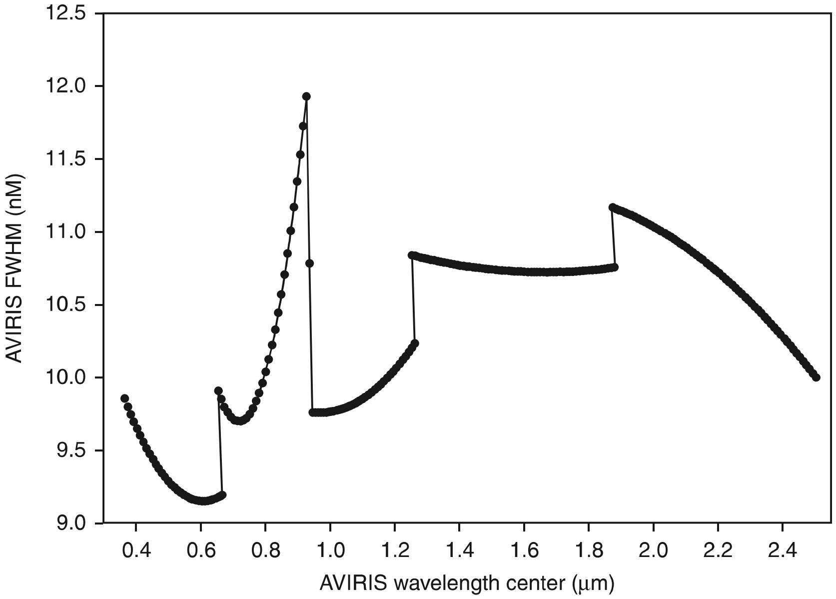

Figure 6 Airborne visible/infrared imaging spectrometer (AVIRIS) spectral response-function characteristics. The sensor exhibits 224 spectral bands with very narrow spectral bandwidths. Notice that the wavelength interval and FWHM values vary across the spectrum. The very high spectral resolution allows improved characterization of measured spectra.

demonstrated that the depth and width of the hydroxyl absorption feature at 220 nm changes with increased soil salinity. Others have found that surface gypsum is highly correlated with the NaCl content in some soils and can be spectrally identified.

Other soil processes can be examined and include soil erosion and deposition (Ben-Dor et al., 2009). Using airborne visible/infrared imaging spectrometer (AVIRIS) data, Hill et al. (1995) used a spectral mixing model with end-member spectra to describe the status of soil erosion. They estimated the relative abundance of parent material and soil particles on the surface. This represents the mapping of erosion state, as it is related to the mixing ratio between developed substrates and components of the parent material.

Another approach to assessing soil erosion involves quantitative assessment of soil chemical properties (Ben-Dor et al., 2009). For example, Hill and Schütt (2000) suggest that organic carbon can be a tracer substance for identifying accumulation areas and relatively stable soil conditions. Stable conditions correspond to higher infiltration and water retention capacity; therefore, erosion and depositional areas can be mapped based on detecting organic carbon. The curvature of the spectral continuum from 0.4 to 1.6 m was used to derive the organic carbon content of soils (Hill and Schütt, 2000). Research has indicated that spectral differences are associated with variations in weathering and natural versus eroded soils (Demattê, 2002).

Other capabilities are also feasible and include soil mapping and classification, extraction of information regarding soil genesis and formation, and assessment of soil contamination and swelling (Ben-Dor et al., 2009). These capabilities are related to assessment of specific soil properties including: (1) presence and absence of primary and secondary silicate minerals; (2) quantification of iron oxides; (3) content, composition, and maturity of organic matter; (4) quantitative estimation of heavy metals; and (5) assessment of soil moisture content.

Imaging spectroscopy is also used in vegetation science and ecology. Its utility is based on assessment of specific physical and chemical characteristics of vegetation. In the visible region of the spectrum, plant pigments absorb radiation and absorption features can be used to assess a variety of plant pigments. In the NIR region, plants exhibit relatively high reflectance and transmission. The distribution of air spaces and the size, shape, and arrangement of cells determine the passage of light through plant leaves and the amount of scatter in the mesophyll layer of leaves. In the SWIR region, leaf moisture and foliar biochemicals influence reflectance, and this region contains strong water absorption features and minor biochemical absorption features.

Variations in environmental conditions can cause variations in chlorophyll production, leaf cellular structure, and leaf moisture conditions. Consequently, variations in these and other canopy characteristics (e.g., leaf area index) can be detected via imaging spectrometer data, and provide an insight into surface/subsurface conditions, as plants respond to soil geochemical, lithological, and structural conditions. Numerous studies have evaluated the use of spectra and the shifting of the red edge to detect plant stress and their response to mineral deposits, lithological changes, and other environmental characteristics (e.g., Collins et al., 1983; Boochs et al., 1990).

Finally, imaging spectroscopy can be used for assessing water in various phases within the Earth's natural systems, and this supports new strategies for hydrological research and assessment of quality and distribution (Green et al., 2006). Remote sensing has commonly been used for the assessment and mapping of inland and coastal water quality conditions. With the advent of spectrometers, atmospheric water-vapor conditions and ice-crystal size variations in snow can be assessed quantitatively (Dozier et al., 2009). This allows distributed water-budget assessment in high-altitude basins that facilitates water management and planning activities.

Each phase of water exhibits absorption features between 400 and 2500 nm. Water vapor exhibits an extremely fine spectral absorption structure, and liquid water and ice exhibit broad molecular absorption bands (Green et al., 2006). This allows spectroscopic separation of the three phases. Consequently, imaging spectroscopy will play an ever-increasing role in hydrological research, as detailed information regarding surface-energy conditions (i.e., albedo) can be used for energy-budget modeling, the update and validation of distributed snowmelt and runoff models, and in assessing water-quality condition and bathymetry in relatively shallow inland and coastal areas. Unfortunately, a chapter on Imaging Spectroscopy was not completed in time for inclusion in this Treatise volume.

3.1.3.3 Microwave Remote Sensing

Unlike optical-based sensors that depend on reflected and emitted radiation from objects and surfaces, microwave sensors collect information from the microwave region of the electromagnetic spectrum with frequencies ranging from 0.3 to 40 GHz. Passive and active sensors exist; however, active sensors play a dominant role.

Numerous sensor types provide a wealth of information obtained at planetary, region, and local scales. Consequently, it is essential to be familiar with the advantages and disadvantages associated with the use of specific microwave sensors. These include radio detection and ranging (radar) altimeters, synthetic aperture radar (SAR), polarimetric SAR, stereo SAR, and interferometric SAR. The choice of a particular sensor and analysis for information extraction is slightly more complicated compared with optical-based sensors, as the backscatter of microwave radiation is dependent on frequency selection, sensor-system imaging geometry, polarization, surface composition and roughness, near-surface structure, and the electrical composition of the surface that determines the amount of the energy reflected, absorbed, and transmitted.

Radar imagery can be qualitatively evaluated using human interpretation techniques. Quantitative analysis is used to produce topographic information (i.e., DEMs) that is routinely utilized by Earth scientists. In addition, the ability to assess deformation patterns resulting from natural (e.g., earthquakes) and anthropogenic events (e.g., oil and ground water extraction) allows new insights into the nature of numerous processes related to landscape evolution and natural hazards. Numerous applications involving geodesy, land cover, ecology, hydrology, geology, geomorphology, and glaciology are possible.

Hensley and Farr, in Chapter 3.3, provide an authoritative treatment of microwave remote sensing in geomorphology. They specifically address the different types of active microwave sensors and relate scale to various geomorphological applications. Microwave remote-sensing principles are also addressed so that users take into consideration the multitude of factors that influence backscatter variations in imagery such as frequency, resolution, polarization, scattering, and penetration. For each sensor, the theory of operation is examined and specific geomorphological applications are presented. This treatment of the topic should provide readers with an insight into the complex nature of matter–energy interactions in the microwave region of the spectrum, while highlighting the wealth of landscape information that can be obtained and utilized by the Earth science community.

3.1.3.4 The Atmosphere and Climate Forcing

The linkages between climate and surface processes have long been established by the geomorphological community. Atmospheric conditions regulate surface energy, temperature, and precipitation. Climate forcing is an active research area and is known to govern process domains, rates of erosion, and the presence/absence of specific landforms. A relatively recent development has been the recognition of the complex interrelationships between climate, surface processes, and tectonics (Molnar and England, 1990; Shroder and Bishop, 2000). This has prompted vigorous debate regarding the magnitude of erosion, role of surface processes, and issues of climate versus tectonic forcing in orogenesis. Investigations into climate–geomorphology linkages require quantitative estimates of atmospheric variables and maps depicting the spatial variability of atmospheric conditions. Such detailed information has not been historically available to geomorphologists. Recent advances now allow a detailed examination of the atmospheric conditions that facilitate climate forcing studies, and remote sensing provides new avenues for geomorphological research.

The moderate resolution imaging spectro-radiometer (MODIS) on the Terra and Aqua satellites can be used to collect a variety of atmospheric parameters. It has a swath width of 2330 km and can nearly provide global coverage of atmospheric conditions using 36 spectral bands ranging from the visible to the thermal region of the electromagnetic spectrum. Specifically, it allows global monitoring of atmospheric profiles, precipitable water-vapor amount, aerosol particles, and cloud characteristics. An atmospheric profile algorithm is used to estimate the atmospheric temperature and moisture conditions. Consequently, the spatial pattern of the atmospheric temperature and moisture variations at a particular level in the atmosphere can be examined. See King et al. (2003) for technical details and a more complete description of data products generated from the sensor.

Other imaging spectrometers can also be used to assess atmospheric conditions. For example, Green et al. (2006) used AVIRIS over Mount Rainer in Washington to assess water vapor content. At the water vapor absorption bands (near 940, 1150, 1380, and 1900 nm), the upwelling radiance at the sensor varies in strength as a function of the column water vapor content. Numerous investigators have found a strong relationship between water vapor and elevation (Green et al., 2006). Consequently, AVIRIS data can be used to generate high-resolution atmospheric moisture maps.

The magnitude of precipitation is another key atmospheric parameter. Satellite remote sensing is an indispensable means of measuring and monitoring precipitation on a global scale (Masunaga et al., 2002). The tropical rainfall measuring mission (TRMM) has made significant contributions to the Earth sciences, as scientists have access to a variety of precipitation information products. This information is critical for water-budget studies involving ground water recharge and extraction, surface runoff and human impact on basin hydrology, water storage and resources in mountain environments, and in the assessment of flooding and flood inundation. Furthermore, this parameter is critical for studying the influence of climate forcing on mountain topographic evolution, studying specific climate systems (e.g., Houze et al., 2007), and validating climate simulations.

Numerous researchers have examined spatial patterns in precipitation in an attempt to quantitatively relate climate to topography, erosion, and specific process domains (e.g., Burbank et al., 2003; Wulf et al., 2010; Bishop et al., 2010). Research indicates a coupling between precipitation and topography (Nesbitt and Anders, 2009) and magnitude variation can characteristically reveal the presence of orographic precipitation and erosion zones that may be related to uplift patterns. For example, Wulf et al. (2010) examined seasonal precipitation gradients using TRMM data to determine their impact on fluvial sediment flux in the Himalaya. They found that the Indian summer monsoon is the main driving force for erosional processes, despite more precipitation falling in the winter season. Similarly, Bishop et al. (2010) used TRMM data to find that the highest amounts of precipitation in the Karakoram occur during the spring by the westerlies (**Figure 7**). They also noted a spatial coincidence between a precipitation anomaly in the Hunza region and increased landscape dissection and steep slopes, suggesting the presence of a high-magnitude erosion zone.

Remotely derived atmospheric information has not been thoroughly utilized in geomorphology and numerous research opportunities exist. For example, an important part of landscape evolution is related to physical and chemical weathering and regolith production. Research has demonstrated links between weathering and surface and atmospheric conditions (Curtis, 1976; Trudgill, 1976). Spatial distribution patterns of air and surface temperature, air and surface moisture, surface mineralogy, and vegetation characteristics should provide insights into the magnitude and distribution of weathering and regolith production. Perhaps modelers might be able to develop new parameterization schemes that incorporate satellite-derived atmospheric and surface parameters. This would significantly improve the ability to account for the spatial variability in weathering and sediment transport. Nevertheless, there would be other difficult issues to address that include accounting for biological processes, acid production, and the integrated influence of climate change that extends beyond the temporal availability of the data.

Atmospheric information is also critical for understanding and predicting the surface-energy budget that governs many surface processes including weathering, moisture availability, erosion and sediment transport. Numerous field studies typically use point station data to obtain measurements of atmospheric conditions, not knowing the degree of variability associated with the shortwave and longwave net radiation flux. Atmospheric conditions, surface albedo and temperature, and topographic information via remote sensing allow more sophisticated modeling that can be used for hydrological and

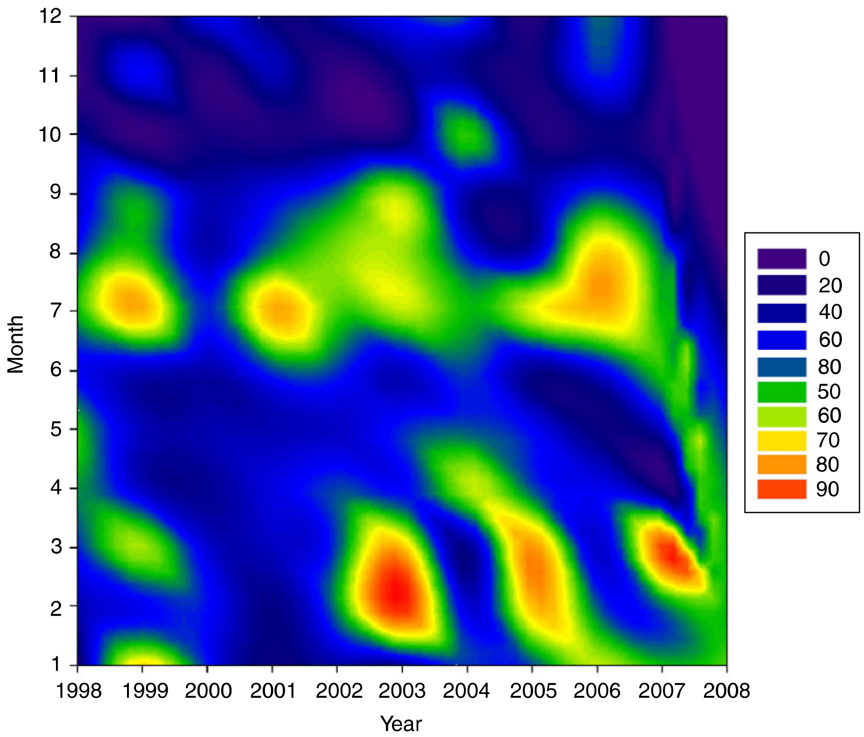

Figure 7 Tropical rainfall mapping mission (TRMM) precipitation data (3B43V6) for the Baltoro-Mustagh region in the Karakoram Himalaya, Pakistan. The temporal variation in cumulative precipitation (mm per month) depicts the influence of the westerlies during the spring and the combined influence of the southwestern monsoon and westerlies during the summer months. TRMM data can also be used to examine spatial patterns in precipitation. Such satellite data allow a spatio-temporal evaluation of precipitation conditions.

glaciological investigations. Consequently, satellite-derived atmospheric information can greatly improve the understanding of many aspects of geomorphological systems. Unfortunately, a chapter on this topic was not completed in time for inclusion in this Treatise volume.

3.1.3.5 Land-Cover Assessment and Mapping

Aerial photography and satellite imagery have been historically utilized to generate land-cover and land-use information. A multitude of new high-resolution and multispectral sensors acquire data that can be used to characterize a wide range of biophysical landscape properties. Collectively, this information can be used for thematic mapping of land-cover characteristics. Research has focused on evaluating the information content within multispectral datasets, evaluation and comparison of pattern-recognition techniques for improved classification of thematic content, and the development of new methodological approaches for data fusion, spectral-feature extraction, spatial-feature extraction, and multitemporal analysis. Although challenges remain with respect to addressing increased data volumes and increased spectral and temporal variability, existing software systems allow routine mapping of fundamental land-cover classes. Thematic mapping and study of land-cover dynamics represent an important component of geomorphological assessment and mapping. Furthermore, land-cover and land-use patterns provide an insight into the magnitude of anthropogenic forcing.

New capabilities include developments in a variety of subdisciplines. For example, data fusion is an approach to mapping and analysis that exploits the power of multiple representations of the landscape. This involves integrating data with different spatial, spectral, and radiometric resolutions. A classic example is merging multispectral satellite data with higher-resolution panchromatic data. In a GIS, multiresolution airborne and satellite data can be fused with a DEM, terrestrial photography, maps, and graphics. Digital mapping can be accomplished by utilizing various feature sets that represent multiple landscape dimensions and perspectives.

Object-oriented land-cover mapping also represents a relatively new development. It first requires meaningful segmentation based on specific criteria to generate spatial entities called objects. Initial segmentation is typically based on information in imagery and DEMs. Numerous approaches to segmentation can be used including homogeneity and shape analysis, region growing, pattern recognition, and rule-based segmentation. Segmentation results are then analyzed via spatial clumping to identify individual homogeneous spatial entities. These objects then serve as a spatial constraint for subsequent analysis. Object-oriented analysis involves computing the attributes of individual objects such as object location, size, shape, and its topological relationships with other objects on the landscape.

Mapping can be facilitated by spatial aggregation and spatial intersection of objects and by identifying unique patterns of object attributes in an *n*-dimensional feature space. This approach is widely recognized as superior to purely pixel-based classification procedures, as it allows the integration of image elements (i.e., tone, texture, size, shape, pattern, site) and the linkage of spatial objects across multiple scales. This approach is also valuable for mapping specific landforms based on the segmentation of terrain units using geomorphometry.

Allen and others in Chapter 3.4 specifically address the issues of land-cover and land-use assessment via optical remote sensing. They highlight the data sources that are valuable for land-cover mapping and review some of the methodological approaches that are routinely utilized. Finally, they provide classic application examples of how land-cover information is used in geomorphology and provide a treatment on land-cover change detection.

3.1.3.6 Near-Surface Geophysics

Remote sensing of the subsurface is commonly required to assess geomorphological systems and to accurately map the three-dimensional extension of landforms and structural features. Subsurface compositional variations and the occurrence of subsurface structures can have a significant influence on surface processes and landscape evolution.

Information on subsurface materials and characteristics can be obtained by passive gamma-ray spectrometry and geophysical techniques such as seismic, gravity, aeromagnetics, electromagnetics, and ground penetrating radar (GPR). Gamma-ray spectrometry may indicate the composition of materials in the upper 50 cm of the surface (Smith and Pain, 2009), whereas gravity, aeromagnetics, electromagnetics, and GPR can be used to assess density, subsurface features, conductivity variations, and depths, respectively (Lane, 2002; Wilford, 2002). Consequently, subsurface lithological variation can be compared with surface morphometry and other biophysical properties to characterize the 3-D nature of landforms. The cost and availability of such subsurface information is currently a serious limitation, as expensive airborne or field surveys are required.

Nevertheless, the use of geophysical techniques in geomorphology crosses many subdisciplines, as revealed by Kruse in Chapter 3.5. She summarizes the relative significance of different geophysical methods in various subdisciplines of geomorphology. She also provides practical advice for prospective users of near-surface geophysics and highlight the importance of reference data collected in the field, in addition to geophysical data. There is a need for the comparison of methods and caution in the interpretation based on forward or inverse modeling. Kruse notes that the uses of near-surface geophysics in geomorphology are not fundamentally different from the uses in other geoscience disciplines, and that geomorphologists would be well served by examining methods and results from tectonic, hydrogeophysical, applied geophysical, and engineering studies.

3.1.4 GIS and Geomorphology

The rapid proliferation of GIT allows improved data management, manipulation, analysis, modeling, and visualization capabilities. Various forms of spatio-temporal data can be stored in GIS databases, and a plethora of software tools allows scientists to effectively study spatio-temporal patterns and relationships.

Such new capabilities represent a substantial evolution in geomorphological assessment and mapping compared with traditional approaches (Bishop et al., 2012). Yet, the traditional approaches of information integration via analytical reasoning, which is the pillar of qualitative interpretation, are poorly represented by statistical metrics and mathematical operators that are commonly used in GIS analysis. Furthermore, the results of GIS-based quantitative analysis and numerical modeling are dependent on numerous factors and simplifying assumptions, and may not be representative of objective measurements obtained in the field. Consequently, conceptual and practical issues need to be recognized, and Bishop et al. (2012) have identified a number of issues that should be considered. These include representation, the predominantly empirical nature of using modern-based GISs, scale, and mapping perspectives. In general, advances in geomorphology have resulted from addressing these issues and utilizing geospatial technologies to address specific problems.

3.1.4.1 Digital Terrain Modeling (DTM)

Quantitative land-surface information is required in geomorphology. A major contribution of remote sensing has been the development and use of passive and active sensors to generate DEMs. A variety of techniques can be utilized for DTM including image photogrammetry, radar or laser altimetry, and interferometric SAR. Photogrammetric applications utilizing Satellite Pour l'Observation de la Terre (SPOT) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data are commonly used by scientists. In the case of SPOT imagery, alternate view perspectives from multiple satellite passes enable stereoscopic representations, whereas the ASTER system relies on forward- and back-looking telescopes to characterize topography through a merged characterization. Similarly, radar imagery and specifically shuttle radar topographic mapping mission (SRTM) data are widely used. The SRTM and ASTER mission objectives were specifically designed to produce a global DEM data product to facilitate Earth science applications. These DEMs have resulted in many new developments to characterize surface morphology and better assess and map the landscape.

More recently, airborne high-resolution LiDAR systems and terrestrial-laser-scanning systems now generate millions of 3-D point measurements. These 'point clouds' must be analyzed and manipulated to ensure accurate interpolation to generate a bare-Earth altitude field. LiDAR high-resolution DEMs allow detailed geomorphometric characterization of the surface and greater mapping accuracy (**Figure 8**). Such data allow developments in geomorphometry to be exploited, whereas the same techniques may not be as useful, given a coarser DEM measurement scale. For example, DEM differencing is an important aspect of change detection suitable for examining spatial patterns of surface dynamics and volumetric analysis, but the availability of high-resolution, geo-referenced elevation grids is critical. Numerous studies have revealed the significance of using an optimum resolution to appropriately characterize geomorphometric parameters for erosion and mapping investigations (Zhang and Montgomery, 1994; Napieralski and Nalepa, 2010).

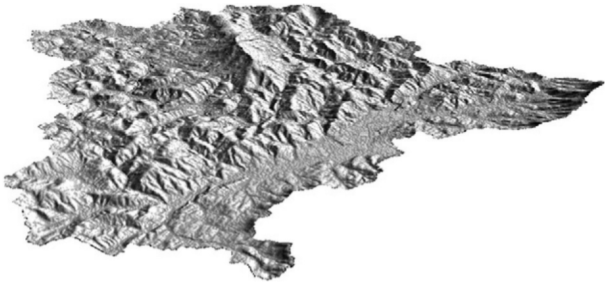

Figure 8 One meter digital elevation model generated from LiDAR data with an average point spacing of approximately 5 m. ESRI terrain dataset generated from original bare-earth LiDAR points from the North Carolina Floodplain Mapping Program. The 1 m DEM was created to enhance hydrographic modeling operations within the watershed. DEM courtesy of Jeffrey Colby, Appalachian State University.

DTM involves many issues related to the nature of data acquisition and sampling, preprocessing, spatial interpolation, quantitative characterization of error and uncertainty, and postprocessing. Evaluation of DTM for geomorphological applications is an active research theme. Wasklewicz and others in Chapter 3.6 discuss the generation and utility of DEMs in geomorphology. They address the technical advances in measuring the topography including laser-scanning, shuttle-based radar, and terrestrial photogrammetry techniques. They also address numerous technical issues that must be accounted for via preprocessing and postprocessing. They correctly acknowledge the need to understand a variety of DTM issues that are critical in analysis and communication of information generated from a DEM.

3.1.4.2 Terrain Analysis

The quantification and analysis of the land surface is called gemorphometry (Pike, 1995, 2000). Geomorphometry plays a central role in studying surface processes and for geomorphological mapping. Consequently, it has been characterized as general and specific geomorphometry, respectively.

Geomorphometry addresses issues of: (1) sampling attributes of land surfaces; (2) geodesy and DTM; (3) DEM preprocessing and error assessment; (4) generation of land-surface parameters, indices, and objects; and (5) geomorphic information production and problem-solving using parameters and objects. Each aspect of geomorphometry represents a research subdiscipline and contributes significantly toward the development of software tools and geospatial technology. Its significance in geomorphology is expected to increase, as it can be used for assessing and mapping geology and tectonics, landform elements and landform, functional units related to water resources and hydrology, process domains, erosion patterns, as well as climate and meteorological conditions (Bishop et al., 2012).

Progress has focused on:

- The development and use of geomorphometric algorithms. New and modified forms of parameters and indices are being developed and evaluated for assessment and mapping. Spatial analysis involves neighborhood operations, subgrid operations, and multiscale analysis. The primary mathematical approach has been statistical analysis and probability theory; however, geostatistics, artificial intelligence, and fuzzy-set theory are increasingly being utilized.
- New software tools and systems for geomorphometric analysis and mapping. A number of programs are specifically designed to compute numerous geomorphometric parameters, although many GISs are limited to basic parameters. Consequently, geomorphometry and mapping can be carried out using ESRI software (Reuter and Nelson, 2009), SAGA (Olaya and Conrad, 2009), ILWIS (Maathuis and Wang, 2009), LandSerf (Wood, 2009), MicroDEM (Guth, 2009), TAS GIS (Lindsay, 2009), GRASS GIS (Hofierka et al., 2009), and River-Tools (Peckham, 2009), just to name a few.
- Existing and new applications. Numerous algorithms and approaches for characterizing spatial variation, scale, landscape position, fuzzy boundaries, and complexity exist, and many landforms and features such as drainage basins and networks, ridges, and peaks can be mapped to various degrees. Nevertheless, researchers have a daunting task of determining which metrics and approaches are best for specific objectives. Geomorphometry has significantly contributed to geological, soil, vegetation, landform, ecological, hydrological, mass movements, hazards, meteorological, and agricultural mapping applications, and new applications are likely to evolve (Gessler et al., 2009).
- Mapping other aspects of the geomorphic system related to climate and tectonic forcing, process domains, and erosion, however, is more complex and may require very different morphometric approaches. For example, quantifying the extent to which geomorphic parameters or landforms and landform elements can be used to assess and characterize tectonic signals, or the influence of tectonics on the landscape, remains a key challenge in the Earth Sciences (Boulton and Whittaker, 2009; Whipple, 2009). A typical approach includes the analysis of drainage basins and patterns, and an evaluation of the longitudinal profiles of bedrock rivers. Asymmetric drainage patterns, elongated drainage basins, and convexities and the presence of knick points are thought to reflect the system response to ongoing tectonic uplift (Jamieson et al., 2004; Boulton and Whittaker, 2009). Other applications, such as the sampling and estimation of surface cosmogenic nuclides, allow estimates of catchment erosion rates using GIS. This requires knowledge of the production rate of various isotopes related to the incoming cosmic-ray flux, which is governed by latitude, altitude, slope, azimuth, and topographic shielding (**Figure 9**).

It is essential that geomorphologists be familiar with geomorphometric parameters and know how to use them for various applications. Wilson and Bishop in Chapter 3.7 provide a treatment of geomorphometry that highlights various parameters and how they can be used for studying geomorphological systems and for geomorphological mapping.

3.1.4.3 Landform Mapping

Historically, landform mapping was primarily a field-based activity, although it has rapidly evolved, given the advent of geospatial technologies and the ever-increasing availability of spatio-temporal data (Bishop et al., 2012). New imagery and DEMs, along with new algorithms and processing approaches, now allow assessment of surface materials, assessment of near-surface conditions using geophysical techniques, and assessment of terrain morphology. These new mapping capabilities, however, bring about new challenges involving theory, concepts, and technology that need to be carefully addressed. This will require new developments in data, representation, analysis, and visualization.

A fundamental issue in mapping is that of spatial complexity and taxonomy, as robust and reliable classification is required for landform mapping. Bishop (2009) addressed this issue and discussed the need for taxonomic criteria that facilitate the classification of volcanic landforms. Spatial complexity was addressed using a generic approach that described the complexity of landform regardless of scale, climate regime, or geological and tectonic setting. This concept is critical for GIS-based landform mapping as formalized taxonomies seem warranted to address the indeterminant nature of landform terminology.

Similarly, the indeterminant nature of landform boundaries is an issue, as many landforms do not exhibit a discrete demarcation in material and form (Burrough, 1996; Lagacherie et al., 1996; Bishop et al., 2012). For example, Deng and Wilson (2008) used fuzzy theory and fuzzy spatial entities to map mountain peaks. Peaks were mapped as multiscale entities with modifiable boundaries. Their approach allowed vague peak entities to be assessed. The approach addresses landform delineation, spatial continuity, and multicriteria definition, all important concepts in landform mapping.

Assessment of the spatial uncertainty associated with process domains and landform mapping is another critical area of investigation. Increasingly, landform mapping is being accomplished by the development and assessment of complex spatial models that inherently incorporate the error that is associated with data, algorithm selection, processing procedures, and model assumptions. There is a need to quantitatively characterize the degree of uncertainty in such mapping models, and selected techniques including artificial intelligence (i.e., neural networks and fuzzy uncertainties) and fuzzy theory can be used to facilitate such investigations. For example, Luoto et al. (2010) produced spatial uncertainty maps based on the agreement between different modeling techniques. The uncertainty maps reflected the reliability of assessing periglacial landforms.

A multitude of studies have focused on improving mapping capabilities for assessing fluvial and hydrological systems (e.g., Schaper et al., 1999; Marcus et al., 2003), glacial and periglacial systems (e.g., Schneevoigt et al., 2008; Kääb and Vollmer, 2000; Frankl et al., 2010), and various aspects of the sediment transfer cascade including mass movements (e.g., Wichmann et al., 2009). Napieralski and others in Chapter 3.8 address the ways in which remote sensing and GIS can be used for mapping a variety of landforms. Specifically, they highlight the numerous forms of data and methods that can be used.

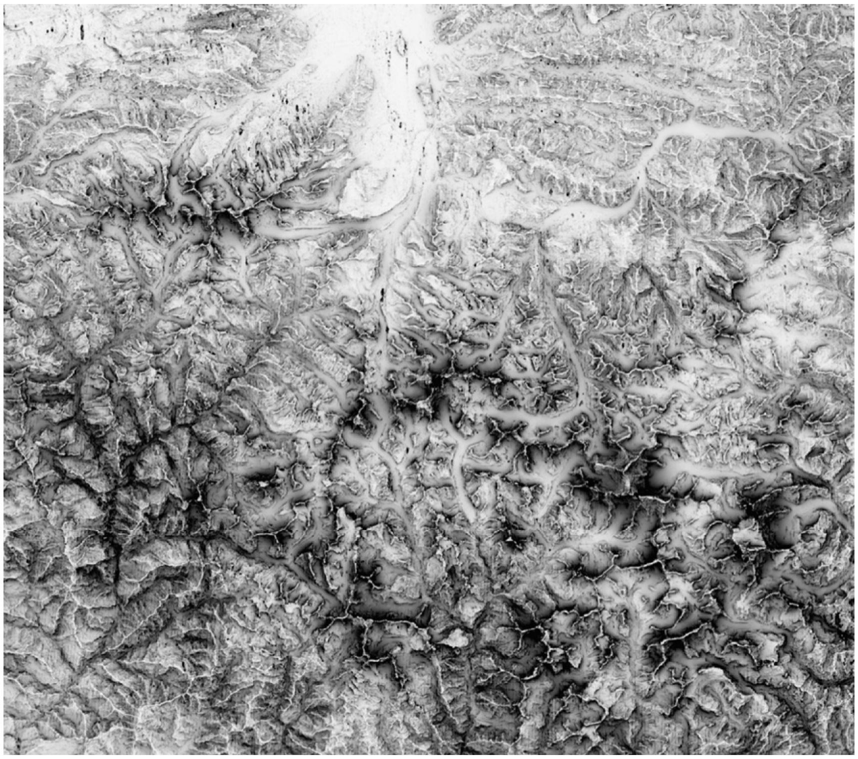

Figure 9 Skyview-factor image over the Mount Everest region in Nepal. The skyview factor represents the degree to which the atmosphere can be viewed, given hemispherical topographic variation. Flat terrain exhibits a skyview factor of 1 (white) and lower values (darker greytones) depict valley bottoms exhibiting more relief. The algorithm examines the relief characteristics around each pixel using an azimuth direction interval out to a specified distance. The magnitude of the parameter is directly related to topographic shielding of incoming radiation. Consequently, this parameter is valuable in depicting variation in the cosmic-ray flux required for cosmogenic-based erosion modeling and in assessing surface irradiance conditions for surface energy-budget modeling, as it governs the diffuse-skylight irradiance. Its evaluation provides new research opportunities in geomorphology, hydrology, and glaciology.

They also cover landslide mapping and relate this to hazard studies. This treatment represents many of the traditional and new forms of analysis that have been used in geomorphological mapping.

3.1.4.4 Spatial Hydrology

Understanding the spatio-temporal complexities of the hydrological system is essential for characterizing geomorphological systems and for the management of water resources. Detailed information is required about the spatial variability of functional units and processes that govern the collection, flow, and storage of water (Beven and Moore, 1993). Consequently, information regarding climate, geology, topography, land cover, soils, and regolith is needed to characterize various components of the system.

Meso-scale information regarding atmospheric moisture and precipitation rates can be obtained with passive and active sensors (e.g., MODIS and TRMM). Spatio-temporal variations in surface-water conditions are assessed by mapping water, snow, and ice/glacier distributions (Bishop et al., 2004; Green et al., 2006; Dozier et al., 2009). Active sonar systems can produce detailed bathymetric data to facilitate volume estimates for rivers and lakes. Remotely sensed data and analysis can also be used to estimate the grain size of the snow, the fraction of each pixel covered by snow, and the amount of radiative forcing caused by absorbing impurities (Dozier et al., 2009).

Satellite gravimetry allows assessment of water mass variations in the cryosphere and subsurface (Rodell et al., 2009; Matsuo and Heki, 2010). Data from the gravity recovery and climate experiment (GRACE) satellite mission can provide monthly estimates of the Earth's gravitational field (Tapley et al., 2004). Time variations in the gravitational field can be used to determine changes in the Earth's mass distribution. Water mass variations represent a dominate signal that can influence the gravitational field (Wahr et al., 1998). Consequently, if the data are preprocessed appropriately, and mass variations due to the atmospheric and tectonic conditions are accounted for, GRACE data can be used to evaluate water mass variations in the cryosphere (e.g., Chen et al., 2007; Matsuo and Heki, 2010) and detect large regional anomalies in ground water fluctuations including the Amazon and ground water depletion in India (Syed et al., 2005; Rodell et al., 2009). Consequently, remote-sensing investigations have already provided new insights into hydrological systems at local, regional, and global scales.

Remote sensing and GIS have also contributed significantly to hydrological studies, given the advent of DEMs and terrain analysis capabilities (Beven and Moore, 1993; Wilson and Gallant, 2000). The production of high- and moderate-resolution DEMs using active sensor systems has markedly influenced hydrological modeling. Numerous topographic parameters directly and indirectly control hydrological and geomorphological processes. In general, these parameters have been classified as primary and secondary (compound) parameters that play a significant role in the spatial complexity of the hydrological system (Beven and Moore, 1993; Wilson and Gallant, 2000). Topographic information is now routinely used for assessing and delineating drainage basins and drainage networks, and DEMs are required for assessing water flow direction and regimes.

Topographic parameters govern a variety of climate and lithological processes including precipitation, surface-energy balance, erosion, deposition, and rock stress fields and strength. These in turn influence specific hydrologic processes and storage including recharge, evaporation, infiltration, soil moisture content, and surface saturation zones. One of the most commonly used hydrologically based topographic parameters or indexes is the wetness index, which is used to determine the effects of the topography on the location and size of saturated source areas (Wilson and Gallant, 2000). Land-cover conditions also govern the magnitude of erosion and infiltration capacity, and remote sensing provides detailed information required for watershed analysis and the prediction of discharge. Detailed mapping of impermeable surfaces and GIS-based modeling of urban expansion represent other aspects of watershed modeling and planning.

Terrain analysis is also critical for assessing precipitation patterns, and topographic parameters have been found to influence precipitation rates. The orographic precipitation mechanism is well understood and results in spatial anomalies and gradients in precipitation magnitude in mountainous terrain. However, valley structure and orientation can also influence precipitation, as atmospheric flow can be topographically directed into basins or regions. This is the case in Asia, where monsoon conditions move further inland due to large glacial valleys that do not restrict air flow inland. Similarly, slope angles and relief also govern precipitation, as these parameters regulate the rate at which the air will be forced upward. In orogens such as the Himalaya, precipitation can vary significantly over relatively short distances. Even a microtopographical variation has been shown to be related to precipitation variations (Sharon et al., 1988).

The surface-energy budget is a critical component of the hydrological system. It regulates ablation, snow melt, evaporation, and transpiration. Energy-budget modeling represents the most rigorous approach for assessing surface-water runoff and basin discharge. This type of modeling is critical for the assessment of water resource potential and can be used to address issues of sustainability. Currently, governments around the world are monitoring drought conditions, snowpack variations, and glacier fluctuations to assess future water supplies. Information related to the key energy-balance parameters can be estimated via remote sensing and numerical modeling including surface irradiance, albedo, and surface temperature. Specifically, the net shortwave radiation component can be assessed as atmospheric, topographic, and surface albedo information is required to predict the direct, diffuse-skylight, and adjacent-terrain irradiance. GIS-based irradiance modeling can be used, and it is feasible to account for multiscale topographic effects. Spectral and surface albedo can be estimated using satellite imagery and bidirectional reflectance distribution models. Similarly, the net longwave radiation component can also be evaluated.

The aforementioned discussion summarizes the many ways in which remote sensing and GIS play a fundamental role in hydrological modeling. Data analysis and spatial modeling provide spatio-temporal information for characterizing the spatial structure of hydrological systems and key parameters. Hydrological modeling, however, is mostly concerned with the flow of water over the surface and in the subsurface (Maidment, 1993). Historically, hydrological modeling has focused on the temporal evolution of systems, characteristically assuming uniform spatial properties for various system components. Spatial hydrology represents the linkage of remote sensing and GIS with hydrological models to more accurately account for the spatio-temporal complexities in the hydrological system.

Maidment (1993) reviewed hydrological modeling independent of geospatial technologies and characterized the nature of such models. They typically focus on surface water hydrology, surface water quality, groundwater flow, and groundwater transport. The spatial components associated with the GIS-hydrological model linkage include watersheds, pipes and stream channels, aquifers, lakes, and estuaries. A treatment of the process mechanics of the fundamental flow systems is beyond the scope of this chapter, although there are several levels of GIS-based coupling that are itemized below.

- Hydrological assessment involves the mapping of hydrological factors that relate to a situation. A classic example is the use of the DRASTIC model for mapping groundwater-contamination potential, which characterizes the likelihood that the groundwater will be contaminated based on point and areal sources of contamination, and topographic and subsurface conditions. It represents the utility of GIS-based spatial modeling and does not utilize any explicit physical laws. Such spatial modeling is highly empirical and the results are also a function of ranking and weighting of information layers.
- Hydrologic parameter determination is a very active research area in hydrology. The objective is to accurately estimate the parameters that go into hydrological models, based on atmospheric, terrain, and land-cover analysis. Many examples have been previously presented.
- GIS-based hydrologic modeling represents a more detailed level of coupling. This is possible, provided that the modeling does not require significant temporal simulations. Maidment (1993) indicates that one- and two-dimensional steady-flow computations may be carried out using GIS-based modeling, although often times, numerous assumptions are used to eliminate or reduce temporal variability. Hydrologic modeling of flood inundation is an example of a 2-D GIS-based hydrological model where the groundwater conditions are not taken into account.
- Hydrological modeling that links GIS-based modeling with hydrological subsystem models accounts for the connection between the surface and subsurface systems to examine piezometric head surface and contamination plumes.

The contributions of remote sensing and GIS to hydrology have the potential to open up new fields of study, as new information and methodologies allow for the exploration of new ways to characterize hydrological systems and processes. The limiting factor is not the ability to characterize hydrological processes mathematically or to solve the resulting equations, but to accurately characterize the model parameters, given their scale dependencies (Maidment, 1993). Consequently, recent developments in geostatistics, object-oriented analysis, geomorphometry, and spatial analysis and modeling have considerably strengthened hydrology. New developments in space–time representation and temporal analysis are also required to facilitate GIS-based hydrological modeling. Unfortunately, a chapter on this topic was not completed in time for inclusion in this Treatise volume.

3.1.4.5 Erosion Modeling

Landscape evolution theories indicate that the topography inherently records the interaction between climatic, tectonic, and surface processes. Consequently, geological and topographic information can be used to assess erosion and topographic evolution. Rather than focusing on empirical relationships, landscape-evolution modeling attempts to formalize the understanding of process mechanics and systems coupling.

Clearly, a better understanding of process–form relationships is needed for developing improved erosion models. Depending on the climatic and tectonic setting, variations in weathering, fluvial, mass movement, and glacial processes make it difficult to accurately assess the magnitude and spatial distribution of erosion and denudation.

Erosion modeling facilitates the understanding of such complications, as models account for the conservation of mass and energy, and are based on a series of mass continuity equations to address the erosion and deposition of rock and sediment. Continuity assumes that the rate of change of altitude is proportional to the volumetric sediment flux.

Uplift should account for isostatic and tectonic forcing components. Tectonic forcing includes the advection of rock mass, given structural controls, and the alteration of rock strength, given topographic stress fields and far-field velocities. The tectonics component requires the integration of mechanical models, as feedbacks exist between the topographic stress field, rock strength, and erosion and uplift (Koons, 1995; Koons et al., 2002). The magnitude of denudation also influences the isostatic compensation, which is a function of the flexural rigidity of the crust and the wavelength of the topography (Gilchrist et al., 1994).

Most models use a flexible parameterization scheme that accounts for the depth of regolith production from weathering (Tucker and Hancock, 2010). Parameterization schemes should account for variations in lithology, precipitation, and surface temperature and moisture conditions. Remote sensing and terrain analysis of surface and atmospheric conditions can be used to generate maps that may be associated with weathering patterns. Key variables include surface irradiance, temperature variation, atmospheric water vapor content, and precipitation patterns. In mountain environments, temperature and precipitation variations may be considerable, given highly variable topography and forcing factors (Barros et al., 2006).

Hillslope sediment flux can be accounted for using a linear or a nonlinear relation with the hillslope gradient. Diffusivity coefficients are commonly used, with different values for different environments.

Bedrock river incision is important in many regions and investigators have utilized the stream-power bedrock river incision law to account for fluvial erosion. In general, the change in elevation is modeled as:

$$\frac{\partial z}{\partial t} = KA^m S^n \qquad [6]$$

where K is bedrock erodability and A is the upstream catchment area that is used as a proxy for discharge. The exponents m and n are constants used to differentiate between the stream power and shear stress-based rules.

Simulations of glacier erosion have also been conducted where erosion is based on basal-sliding velocity and ice thickness (MacGregor et al., 2000; Tomkin and Braun, 2002; Pelletier et al., 2010). An abrasion model (Hallet, 1979) can be used such that the rate of erosion is

$$\frac{\partial z}{\partial t} = -au_s^b \qquad [7]$$

where u_s is the basal sliding speed, and a and b are empirical coefficients usually set to 1 or 2. Basal sliding is primarily dependent on the basal shear stress, τ_b, and a bed-friction parameter. Simulations of glacier erosion demonstrate the complexity associated with relating process to form as glacier erosion can enhance or reduce relief and controls valley spacing and slope variability (Harbor, 1992; Bishop et al., 2003; Tomkin and Braun, 2002; Pelletier et al., 2010).

Although such landscape-evolution modeling could be implemented in a GIS (numerous issues do exist), most models for orogen evolution simulations exist outside of GIS environments. Common GIS-based erosion models focus on soil erosion modeling, given relatively mild to moderate topographic conditions. Soil erosion and sediment transport studies are important in agriculture, water quality, and sediment budget modeling, and in determining the magnitude of anthropogenic forcing. Geospatial technologies are ideally suited for soil erosion modeling and numerous models exist that use different sediment transport equations. Mitasova and others in Chapter 3.9 describe different types of erosion models and provide a physical and mathematical foundation for understanding their ability to predict the magnitude and spatial distribution of soil erosion over the landscape. Special emphasis is on using existing GIS-based erosion models and the visualization of erosion patterns.

Ultimately, remote sensing and GIS can provide new information that can be used to develop more rigorous parameterization schemes for erosion modeling. Geomorphometric characterization is required at each time interval to drive process mechanics and process domain states, such that modeling allows parameters, processes, and system characteristics to be mapped. Further advances in GIS space–time representations and formal process–form linkages are urgently needed to facilitate improved GIS-based erosion modeling.

3.1.4.6 Natural Hazards

Advances in remote sensing, GIT, and numerical modeling have greatly improved the ability to assess a variety of natural hazards. To date, remote sensing and GIS are routinely used for assessing volcanic, earthquake, flood, slope stability, meteorological, and other environmental hazards. Given population growth and rapid environmental change, extreme hydro-meteorologic events are expected to increase, thereby causing a higher frequency of hazards.

The literature is replete with research investigating the use of remote sensing and GIS technology for landslide inventory, slope-failure susceptibility mapping, and landslide hazard assessment. Researchers are actively involved with developing, testing, and validating new GIS-based spatial models to predict slope failures in order to keep landslide hazards from becoming disasters in highly populated areas. The methodological approach is typically based on empirical relationships or heuristics, statistical analysis, and the use of deterministic physical-based models. Carrara and Pike (2008) indicated that despite the variety of approaches, our abilities to spatially predict slope failure and hazards are based on unsuitable data, lack of numerical modeling, or improper characterization of processes in slope-failure modeling.

A classic GIS example involves the common approach of utilizing a criterion-weighted scheme based on controlling/triggering factors that include topographic parameters, lithology, land cover, and other environmental variables. These factors are assumed to be causative and are subjectively ranked based on knowledge of the location and existing inventory information. Spatial overlay and weighting of GIS layers are used to produce a composite index that is assumed to be related to slope-failure susceptibility. Such GIS-based empirical approaches have significant limitations as key causative factors/variables involving earthquake activity, rock strength and structure, topographic stress fields, soil depth, cohesion and moisture, and climate forcing factors (precipitation and wind direction) are not usually accounted for. It is important to realize that many of these factors are dynamic and not accurately characterized by static cartographic representations using an ordinal measurement scale. The weighting schemes also do not necessarily portray the relative importance of selected processes and the dominance of site-specific feedback mechanisms.

Other more sophisticated spatial analysis and pattern recognition approaches involving geostatistics and artificial intelligence techniques have also been evaluated, although it is essential to recognize the difference between characterizing spatial and nonlinear patterns and process-based modeling based on fundamental physics and rock geomechanical properties. Given the numerous approaches, both qualitative and quantitative, remote sensing and GIS technology have promoted more quantitative slope-failure studies. Research indicates that there is a high degree of uncertainty with respect to a dominant GIS-based approach to landslide-hazard prediction (Carrara and Pike, 2008), as research tends to focus more on investigating the method or technology rather than focusing on inventories and causative factors. GIS data manipulation cannot be expected to accurately characterize key parameters and processes. GIS spatial analysis may potentially produce new information that can help provide an insight into better understanding mass-movement processes and generate improved predictive spatial patterns. This most likely will require an emphasis on the generation of new causal factors and their integration into GIS-based numerical models.

Another key example of the role of remote sensing and GIS in hazards assessment is in characterizing flood magnitude and inundation. Numerous types of flooding around the world pose various risks to populations and infrastructure. Flash, management-induced, and catastrophic flooding (caused by landslide break-out floods and glacier hazards) can all drastically alter the landscape and create flood disasters in more populated areas. For example, in the spring of 2010 in the Hunza region of Pakistan, a large landslide blocked the Hunza River. Given the relatively large river discharge and the increasing meltwater contributions by glaciers in the region, the water impoundment grew at a significant rate. Multi-temporal satellite imagery was used to monitor the progress of the rapidly growing Lake Gojal (**Figure 10**). When combined with topographic data and discharge information, the water volume and spill-over time can be accurately predicted. It is still slightly unclear as to the reasons why a catastrophic breakout flood did not occur, although landslide experts speculate that it is probably due to remobilized lake clays imbedded with boulders greater than 10–20 m, making an ideal lake dam.

Given the complexity of assessing various types of natural hazards, it is reasonable to assume that an integrated approach involving the use of numerical modeling, field data and mapping, and remote sensing may be required. Pelletier et al. (2005) used this approach for flood-hazard assessment on alluvial fans. Raster-based hydraulic modeling, satellite-image change detection, field mapping of recent flood inundation, and surficial geological mapping were used to characterize specific spatial details that are lacking in standard GIS approaches. Model predictions of flood inundation and flow depths were tested against field and satellite-based flood maps for two extreme events. They were able to predict spatially complex flood hazards that strongly reflect small-scale topographic and geologic conditions.

Geomorphologists typically address the issue of using remote sensing and GIS from a specific hazard susceptibility perspective, although this is only the first phase or component in a series of steps and analyses that are required for hazards assessment and disaster risk management. Chapter 3.10 by van Westin provides a comprehensive treatment of this topic, highlighting the significance and difficulty of assessing specific natural hazards, but also incorporating multihazard assessment as part of a system to understand and manage complex cascading hazard influences. Specifically, van Westin describes the importance of the integration of approaches for hazards assessment and the need to conduct hazard and risk assessments at different scales, from global to community levels. van Westin reveals that each scale or level of analysis has its own objectives and spatial data requirements for hazard inventories, causal factors, and elements at-risk mapping and database development. van Westin also addresses vulnerability assessment approaches. Collectively, his treatment reveals that very little research has been conducted on establishing

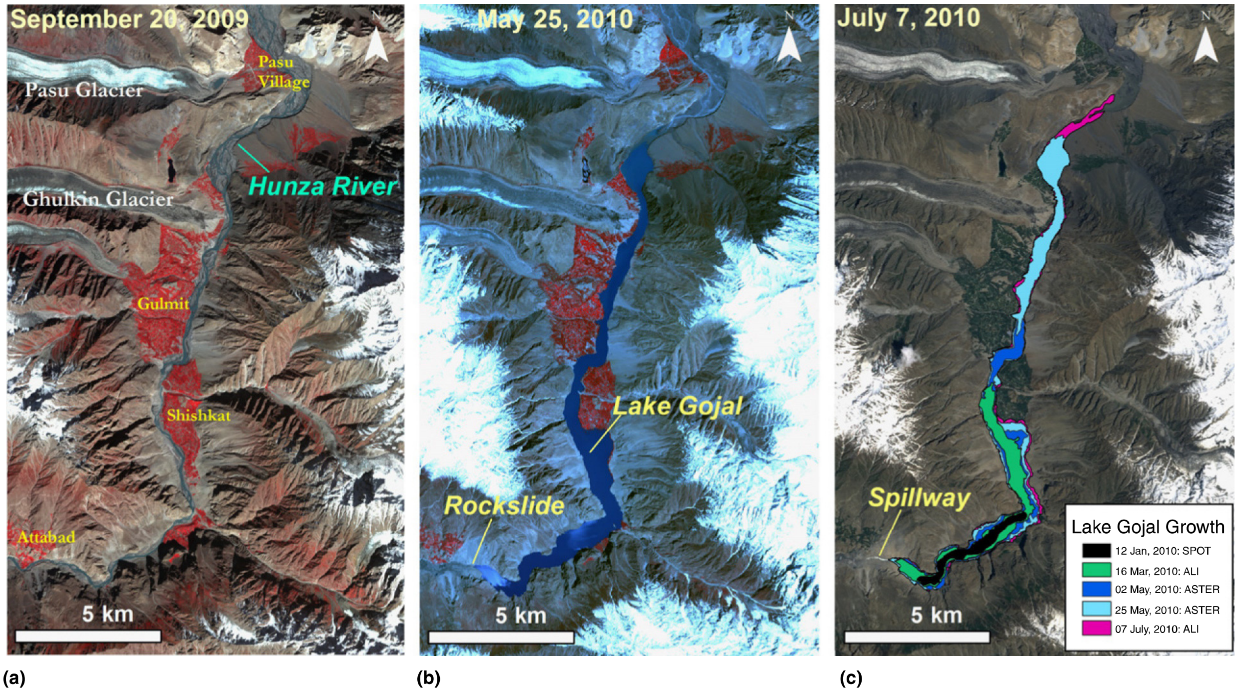

Figure 10 Development of Lake Gojal. (a) Prerockslide ASTER FCC image mosaic of the Hunza Valley. Red represents vegetation, mainly agricultural fields associated with villages. (b) ASTER false-color image 4 day before spillover. Note extensive late spring snowfields and glaciers feeding Lake Gojal. (c) Advanced Land Imager (ALI) near-true-color base image, 7 July 2010, showing the growth of Lake Gojal based on SPOT, ALI, and ASTER. Reproduced from Kargel, J.S., Leonard, G.J., Crippen, R.E., Delaney, K.B., Evans, S.G., Schneider, J.S., 2010. Satellite monitoring of Pakistans rockslide-dammed Lake Gojal. Eos 91(43), 394–395, with permission from AGU.

complete GIS-based multihazard assessments, and that geomorphologists typically focus on evaluating individual hazard types. Although geospatial technologies serve as a basis for hazard and risk assessment, the scientific advances in hazards and risk assessment have remained in the scientific community and have not effectively reached end-users such as planner, managers, and policy-decision makers.

3.1.4.7 Visualization

Visualization is an emerging science that represents research developments in cartography, computer graphics, computational geometry, cognitive science, and psychology (Gahegan, 2000). It is used in a variety of ways to view imagery, integrate information, view spatial and temporal patterns, and interactively examine abstract-data-spaces and numerical simulations. In the Earth sciences, many have recognized the significance of visualizing and perceiving patterns of structure, processes, features, and relationships, in an attempt to validate analysis and modeling approaches and understand many concepts in geomorphology regarding processes, landforms, and system dynamics. With the advent of rapidly improving computer and visualization technologies, a trend has emerged involving more human–computer interaction that exploits the significance of the human visualization system.

In general, visualization is the interaction between computers and humans based on a graphical-user-interface environment that makes use of a variety of visualization techniques. In the geosciences, visualization is used in a variety of ways, and Earth scientists need to be familiar with visualization techniques suitable for working with specific data sets and applications. The major functional uses can be categorized as follows, although these are not necessarily mutually exclusive.

- Exploratory visual analysis (EVA). The goal is to explore the nature of the data such that spatial and temporal relationships and structure become apparent. This is analogous to data mining or knowledge discovery and is closely related to finding statistical anomalies in the data. Classic examples include visualizations of scatterplots and spectral-feature spaces in remote sensing. Such visualizations allow the exploration of spectral end-members that can be used in linear and nonlinear spectral mixing to facilitate accurate mapping of surface composition and assessing the composition mixture of materials that influence surface processes (e.g., surface energy budget, ablation).

  A critical EVA example in geomorphology is visualizing data validity and uncertainty. DTM and the accuracy of DEMs is a critical first step toward meaningful terrain analysis. Three-dimensional perspective viewing of the landscape using anaglyphs or fly-by simulations can be effectively utilized to detect high-frequency errors in DEMs and low-frequency patterns caused by spatial interpolation algorithms. Similarly, the use of pattern-recognition algorithms such as neural networks and fuzzy classifiers can be used to generate fuzzy uncertainties or likelihoods of accurate land-cover or surface matter classifications. These approaches and quantitative measures communicate the concepts of uncertainty, error, validity, or probability.

A geomorphometry example of EVA involves the exploration of scale dependence and prediction of spatial patterns in understanding complex landscapes. Surface parameter magnitudes such as relief, slope, and other important multiscale topographic parameters are dependent on the computational scale of analysis (Bishop et al., 2012). Consequently, visualization of magnitude-scale relations and distribution must be explored to determine the appropriate scale. Spatial scale dependence involves analysis and display to determine the scale of spatial autocorrelation and the directional fabric of the topography. Semivariograms can be used to characterize scale dependence and the anisotropic nature of the topography, although visualization is required to appropriately assign semivariogram models to experimental variograms in order to view simulated spatial patterns (Webster and Oliver, 2007). Furthermore, visualization is critical in an attempt to understand the anisotropic nature of topography caused by various landscape evolution components, as erosion, deformation, rock strength, and faulting govern the directional dependence. To date, this aspect of EVA in geomorphometry is yet to be fully exploited, although the potential for new knowledge generation and new theory exists.

- Visual analysis and modeling. A strong empirical basis is associated with the use of geospatial technologies for analysis and modeling (Bishop and Shroder, 2004b; Deng, 2007; Bishop et al., 2012). Whereas this provides for flexibility in developing metrics, software tools, and new algorithms and analysis approaches, it also raises important questions concerning the validity of analysis and the use of geomorphological information in integrative science.

  Spatial analysis commonly relies on an index approach to characterize various types of landscape information. These indices or metrics are generally based on a association with spatial position or a topographic parameter, although they do not adequately characterize process mechanics, scale dependencies, or temporal dynamics. Furthermore, manipulations of these indices are based on concepts of ranking, weighting, membership, prototypicality, scaling, thresholding, heuristic rules, and additional empirical coefficients that can be used to alter the spatial extent of analysis results. Whereas these metrics have value in terms of flexibility to address issues associated with semantic meanings, spatial uncertainty, subjective interpretations, data integration, classification, and variable definitions, the results can be highly variable. Visualization is required to evaluate the magnitude of index/metric values and determine whether or not such patterns actually represent 'reality' (i.e., morphology, physical properties, genetics, dynamics, landforms). Although new spatio-temporal information can be potentially generated in this way, spatial patterns and the delineation of boundaries and zones must be carefully examined to determine the sensitivity of combinations of parameters. Consequently, visualization is required for adequate and accurate analysis and information production.

  Finally, numerical modeling of climate, surface processes, and tectonics can provide valuable insights into erosion, relief production, feedback mechanisms, and the role of surface processes in landscape evolution. Animations of simulations can provide three-dimensional perspectives on the nature of polygenetic evolution and the genesis of landforms. Visualizations of the temporal dynamics of system-critical parameters such as precipitation, surface-sediment flux, influx of mass due to uplift, and topographic constraints can be very useful for evaluating existing representations of process mechanics and dominant forcing factors. Consequently, visualization will play an ever-increasing role in fundamental analysis and modeling efforts.
- Visual Synthesis. Visualization approaches that allow an evaluation of various types of thematic information can facilitate geomorphological studies. Classic examples include examination of false-color composite images to facilitate geological and land-cover mapping. Spatial overlay and the use of symbols, color, transparency, and material properties can be used to depict a variety of landscape conditions. In essence, geomorphological mapping represents a visual synthesis of landscape conditions, as traditional and modern-day geomorphological maps are commonly generated based on the integration of information reflecting climatic, geological, morphometric, pedogenic, land cover, and geochronological variation. Bishop et al. (2012) provided a treatment of the use of geospatial technologies for geomorphological mapping, and indicate the role of visualizing and integrating a multitude of data types for assessing geomorphological conditions. Given the complexity of polygenetic evolution and the general lack of standard protocols for information integration and mapping, new techniques and cartographic approaches seem warranted, as there are different integration requirements based on a variety of mapping perspectives.
- Presentation. Numerous techniques and approaches can be used for presenting information. These techniques and products include traditional graphic products such as cross sections, profiles, images, maps, animations, virtual globes, and virtual realities. Effective communication and dissemination of geomorphological information to planners, managers, and policy makers is a central theme. This aspect of visualization is essential to promote and facilitate the use of scientific information in the decision-making process.

Geomorphological research has been greatly facilitated by rapid advances in geospatial technologies and augmented realities. Chapter 3.11 by Smith and others provides a more detailed examination of some fundamental aspects of visualization in the geosciences. Specifically, they provide examples of techniques and approaches that allow various aspects of geomorphology to be effectively studied. Important examples involving remote sensing and terrain analysis are included. The treatment clearly demonstrates that visualization techniques and approaches are valuable in Earth science investigations.

3.1.5 Conclusions

The rapid advancement of geospatial technologies has had a profound effect on the discipline of geomorphology. Remote sensing and GIS studies are now commonplace in geomorphological investigations, as a better understanding of surface processes and landscape evolution is sought. Earth scientists are increasingly using new spatio-temporal datasets and GIS technology for analyzing and modeling various aspects of geomorphological systems and for addressing conceptual and practical issues (i.e., scale dependency, process-form and process-pattern relationships, digital geomorphological mapping, landscape evolution modeling, natural hazard modeling).

The 41st Binghamton symposium highlighted many of the aforementioned developments in geomorphology related to geospatial technologies. The delegates were amazed at the rapid evolution of geospatial technologies and were interested in the many new ways to study geomorphological systems and facilitate practical-problem solving. Nevertheless, the delegates realized the difficulty of effectively utilizing new data and analysis/modeling approaches, because the effective use of remote and GIS in geomorphology requires multidisciplinary domain knowledge including radiation transfer, matter/energy interactions, sensor-system characteristics, mathematical underpinnings of algorithms, analysis approaches, models, and Earth science. It is not possible to push a button and obtain the desired results, as expertise and time is required to effectively produce accurate information. It is also essential to recognize the inherently empirical nature associated with using GIS in geomorphology (Bishop et al., 2012). Consequently, it is now important for geomorphologists to take remote sensing and GIS coursework.

Clearly, the incorporation of remote sensing and GIScience investigations into geomorphology has greatly contributed to the quantitative evolution in geomorphology, compared with its more qualitative beginnings. Geospatial technologies have revolutionized the way in which scientists study the Earth, and quantitative analysis and modeling of the landscape offer many new research opportunities. It should be kept in mind, however, that qualitative information derived from the field and via human interpretation of data can contribute greatly to the interpretation of quantitative results. The inherent digital and quantitative nature of modern-day analysis should be carefully examined with respect to GIS-based empiricism and the ability to produce repeatable results. Only through quantitative formalization of geomorphological concepts and theories can such repeatable results be expected, which will go a long way toward establishing geomorphology as a required component in integrated science. Advances in remote sensing and GIScience contribute to this important goal.

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Biographical Sketch

Dr Michael P Bishop is a professor and Haynes Chair in Geosciences in the Department of Geography at Texas A&M University. He received his PhD from the Indiana State University (1987) in physical geography with a focus on geographic information science (GIScience). His areas of expertise are in remote sensing, geographic information systems (GIS), geomorphometry, numerical modeling, and mountain geomorphology. He has published more than 30 articles in scientific journals, three books, and numerous book chapters on topics including radiation transfer, image and terrain spatial analysis, surface processes and landforms, climate and glacier change, and landscape evolution modeling. Furthermore, he has presented more than 200 national and international professional papers on various remote sensing, GIScience, and mountain geomorphology-related topics. Financial support for his research has been obtained through the National Geographic Society, National Science Foundation, NASA, DOE, USGS, and numerous foundations. His current research is focused on the use of satellite imagery and terrain analysis for characterizing surface processes and features in complex mountain environments.