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Applications of remote sensing in geomorphology

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Abstract: Remotely sensed imagery has been used extensively in geomorphology since the availability of early Landsat data, with its value measurable by the extent to which it can meet the investigative requirements of geomorphologists. Geomorphology focuses upon landform description/classification, process characterization and the association between landforms and processes, while remote sensing is able to provide information on the location/distribution of landforms, surface/subsurface composition and surface elevation. The current context for the application of remote sensing in geomorphology is presented with a particular focus upon the impact of new technologies, in particular: (1) the wide availability of digital elevation models; and (2) the introduction of hyperspectral imaging, radiometrics and electromagnetics. Remote sensing is also beginning to offer capacity in terms of close-range (<200 m) techniques for very high-resolution imaging. This paper reviews the primary sources for DEMs from satellite and airborne platforms, as well as briefly reviewing more traditional multispectral scanners, and radiometric and electromagnetic systems. Examples of the applications of these techniques are summarized and presented within the context of geomorphometric analysis and spectral modelling. Finally, the wider issues of access to geographic information and data distribution are discussed.

Key words: DEM, geomorphology, GIS, magnetics, model, process, reflectance.

I Introduction

Geomorphology is that part of physical geography that deals with the form of the Earth's land surface and the processes that act upon it. Geomorphologists are therefore concerned with the *morphology* (ie, shape) and *composition* of the land surface and use this information to determine presently operating processes, as well as postdicting prior landforms (and the events that formed them) and attempting to predict future land surface change (and events). Bauer (2004) identifies the focus of geomorphology to be upon landform description/classification, characterization of dynamic processes and the association between landforms and processes. Remote sensing is well placed to assist in the investigation of these foci through its application in four primary areas: (1) location and distribution of landforms; (2) land surface

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elevation; (3) land surface composition; and (4) subsurface characterization. While historically the large areal coverage and relative low cost of data acquisition has encouraged the extensive use of remote sensing, contemporary applications place it as a core geomorphological data source.

Millington and Townshend (1987) reviewed the application of satellite remote sensing in geomorphology, and this paper has taken the opportunity to use their study as a baseline from which to establish the progress that has been made over the intervening period. They focused upon the spectral sensitivity and spatial resolution of active satellites, noting the use of absorption features in mapping terrain. They also note the relatively recent emergence of thermal infrared (Landsat TM) and microwave (primarily on Seasat) remote sensing, as well as the 'potential' for hyperspectral imaging and digital processing. Figure 1 reproduces their graphic illustrating geomorphic applications with respect to temporal and spatial resolution; we have updated this to reflect the current situation. We discuss implications in the conclusions.

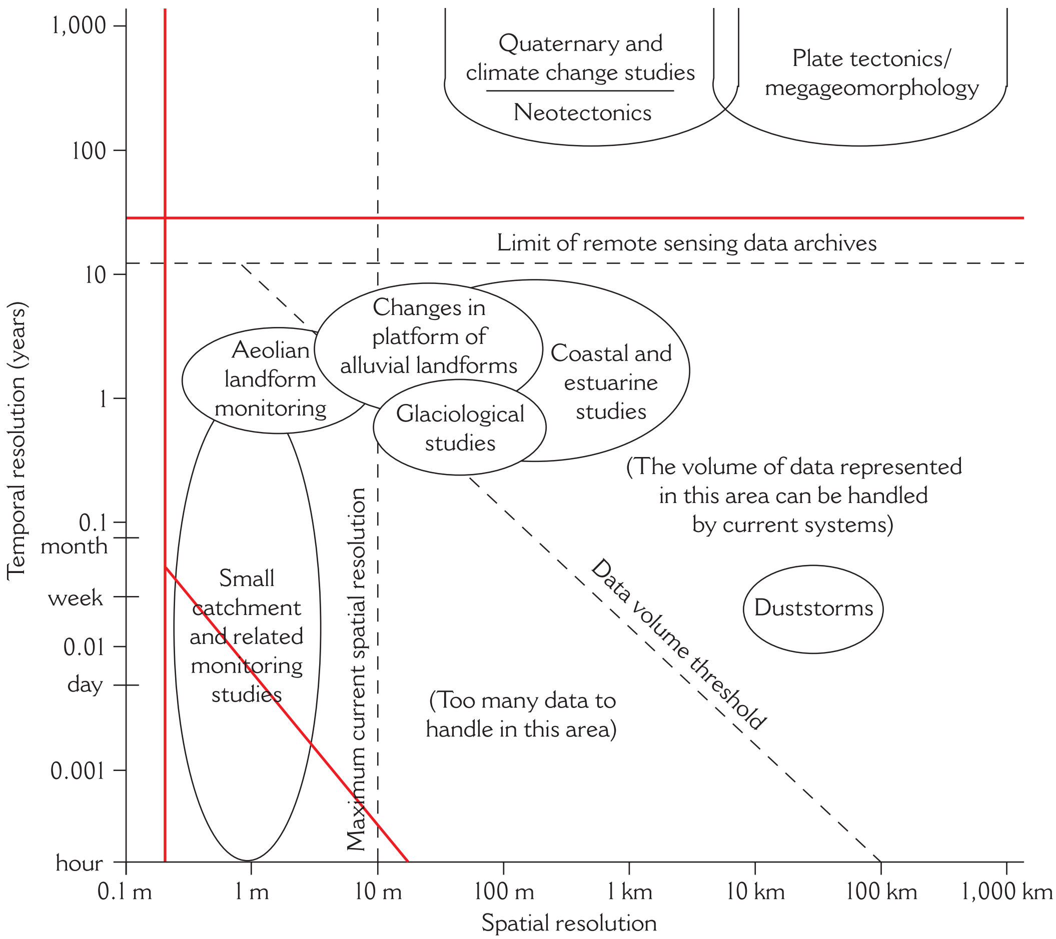

Figure 1 Constraints of spatial and temporal resolutions of satellite sensors upon geomorphological research. This figure has been redrafted from Millington and Townshend (1987), with dashed lines showing their assessment and solid lines updated to reflect current sensors

Set within this context, the earliest geomorphological use of remote sensing involved the qualitative interpretation of aerial photography, with later quantitative photogrammetric exploitation. The proliferation of 'softcopy' digital photogrammetric systems has meant that aerial photography remains an important data source (Fryer *et al*., 2008). However, the greatest use of remote sensing, in terms of data volume, has been through the acquisition of satellite imagery. This was initially realized through the Landsat programme where, for the first time, regional coverage afforded synoptic views of the landscape (eg, Short and Blair, 1986). Early Landsat imagery was often not entirely suitable for particular applications as the low spatial and spectral resolutions, at visible and near infra-red (VNIR) wavelengths, meant that limited information on terrain morphology and composition was available, with little information on subsurface materials given that reflectance is controlled by the upper few microns of the surface. Indeed, recommendations on satellite configuration were developed in order to maximize the surface response from morphology. Millington and Townshend (1987) identify the key use of Landsat TM and SPOT and, prior to the millennium, remote sensing began to deliver on the promised application of microwave wavelengths through RADARSAT and ERS-1/2. Yet it is only in the last 10 years that there has been a move towards the original technical 'frontiers' envisioned by Millington and Townshend with the delivery of commercial high-resolution satellites (eg, IKONOS, Quickbird, GeoEye and WorldView), hyperspectral (eg, Hyperion), thermal (eg, Landsat ETM+, ASTER) and the continued deployment of radar (eg, ENVISAT, RADARSAT-2, Terra SAR-X).

During this period geomorphology has also matured as a subject. Bauer (2004) considers it to have moved from a *quantitative/systems phase* in its development to a *unification phase* indicative of a 'modern science'. This reflects a shift from the quantitative description and use of general systems theory to understand landforms towards an introspective reflection of a range of complex conceptual ideas, as well as multidisciplinary interactions (eg, with Earth and engineering sciences). Current frontiers remain an understanding of scale and the operation of hierarchical and invariant processes, as well as anthropogenic influences upon the landscape. Technology plays a key role, with remote sensing, and the related areas of GIS and computational methods, at the forefront. As a result, geomorphologists are concerned with mapping landform distributions, quantifying the composition (both surface and subsurface) of landforms (and their change over time) and extracting their morphology (as elevation). Elevation has become one of the most successful remotely sensed data products over the last decade, a result of the use of new technologies for its measurement and wide application by geomorphologists. While multispectral remote sensing has been able to provide information on surface composition for some considerable time, it is only relatively recently that morphology has been readily available, on a repeat basis and at a variety of scales (both local and global).

This paper therefore briefly summarizes the satellite and airborne systems from which data are currently used by geomorphologists, before outlining (with examples) the principal areas of application to geomorphological research. We discuss geomorphometric analysis and spectral modelling, with a particular focus upon terrain morphology. A brief discussion of data delivery to both researchers and end-users is provided, before concluding with implications for the future of remote sensing in geomorphology.

II Remote sensing technologies

Table 1 summarizes the principal satellites and sensors currently used for earth science applications. While we note that surface morphology and composition are of primary interest to geomorphologists, the remote sensing imagery *products* of interest are either

Table 1 Primary satellite systems

Sensor	Satellite	Wavelengths	Spatial resolution (m)	Bands
TM	Landsat	VNIR	30	6
		Thermal	120	1
ETM+		Panchromatic	15	1
		VNIR	30	6
		Thermal	60	1
Hyperion	EO-1	Hyperspectral	30	220
ALI	EO-1	Panchromatic	10	1
		VNIR	30	9
	DMC	VNIR	32/22/4	3
	RapidEye	VNIR	5	5
ASTER	Terra	VNIR	15	3
		SWIR	20	6
		Thermal	90	5
AVHRR	NOAA18	VNIR	1100	6
		Thermal		
MODIS	Terra/Aqua	VNIR	250/500/1000	16
		SWIR		4
		Thermal		16
HRG	SPOT5	Panchromatic	5/2.5	1
		VNIR	10	3
	IKONOS	Panchromatic	1	1
		VNIR	4	4
	Quickbird	Panchromatic	0.6	1
		VNIR	2.5	4
	Geoeye	Panchromatic	0.4	1
		VNIR	1.65	4
	Worldview	Panchromatic	0.5	1
KH1-KH6	CORONA	Panchromatic	up to 1.8	1
ASAR	Envisat	Microwave	30	2
	ERS1/2	Microwave	30	1
	TerraSAR-X	Microwave	1/3/18	1

surface elevation or surface reflectance. These often overlap between sensors and we have therefore organized our discussion based upon the primary wavelengths recorded by the sensor and their spatial resolution.

1 Satellite imagery

Historically, the geomorphological use of satellite imagery has largely been driven by the deployment of a range of medium-resolution sensors, moderated by their cost and availability. Yet, as Figure 1 clearly demonstrates, the requirements of geomorphologists vary with respect to the spatial and temporal resolution of the sensors. Cost and availability remain important issues as imagery from high-resolution sensors is not only more expensive, but also less likely to cover an area of interest. Therefore, while launched prior to 2000, Landsat 5 TM, Landsat ETM+ and Terra ASTER remain significant resources due to their satisfactory repeat coverage (for monitoring), large scene size and low cost of entry. This is not withstanding battery problems with TM during 2007 (http://landsat7.usgs.gov), the scan line corrector problem with ETM+ (http://landsat7.usgs.gov) and inter-instrument drift with ASTER (http://asterweb.jpl.nasa.gov). Of significant importance for studies monitoring the change of geomorphic environments is the announcement that the Landsat archive of imagery dating back to 1972 is now freely available (http://landsat7.usgs.gov). At lower spatial resolutions, both AVHRR and MODIS remain useful reconnaissance systems, while their high temporal resolutions allow repeat imaging of rapidly changing environments.

Higher spatial resolutions, usually at the cost of spectral resolution and the number of multispectral bands, are obtainable from a variety of commercial satellites. These include SPOT 5, IKONOS, Quickbird, WorldView and GeoEye, which afford spatial resolutions (from the panchromatic band) similar to aerial photography. With the declassification of CORONA imagery, high spatial resolution panchromatic imagery is available for the period 1960–72.

The largest change in data collection has been the availability of surface elevation data which can be derived using a variety of techniques, including photogrammetry, radar/laser altimetry and interferometric synthetic aperture radar (IfSAR; see Palmann *et al*., 2008, for a recent review). These are commonly made available to the end-user as a gridded digital elevation model (DEM) where elevation is sampled on a regular grid. The National Imagery and Mapping Agency (NIMA) have developed a set of standards for terrain data (Table 2) in support of military applications (Digital Terrain Elevation Data; DTED). Geomorphologists should be aware of this classification system as it is notionally used by manufacturers as a measure of 'quality' through the use of spatial resolution as a proxy. Table 3 lists the reported spatial resolution and vertical accuracy of the DEM products noted below.

Table 2 DTED summary of DEM products (*source*: Federation of American Scientists)

DTED level	Post spacing (sec)	Nominal ground resolution (m)
1	3.0	100
2	1.0	30
3	0.33	10
4	0.11	3
5	0.37	1

Photogrammetric applications of satellite imagery are routinely available through the acquisition of either repeat-pass or single-pass (using a second fore/aft sensor) stereo-imagery. Perhaps the most successful implementation for geomorphologists is on board ASTER (eg, Kamp *et al*., 2005) which employs an aft-looking sensor that is automatically processed to a DEM. So successful has ASTER been at capturing stereo imagery that a single global DEM (83°N–83°S) has been assembled (http://www.gdem.aster.ersdac.or.jp) and this will provide a complementary data set to the Shuttle Radar Topography Mission (SRTM; see below).

The application of radar and laser altimeters (active ranging systems) has been more limited within geomorphology due to the low spatial resolutions, although there has been successful regional monitoring of the Arctic and Antarctic (Bamber, 2006). The notable exception is the Mars Orbiter Laser Altimeter (MOLA) on-board Mars Global Surveyor which successfully operated over a two-year period. This led to the creation of a global DEM of Mars (http://wwwpds.wustl.edu/missions/mgs/mola.html), at a nominal spatial resolution of 440 m, which has seen extensive use in planetary geology and geomorphology. More recently both the High Resolution Stereo Camera (HRSC; on Mars Express) and the High Resolution Imaging Science Experiment (HiRISE; on Mars Reconnaissance Orbiter) have been

Table 3 Specifications of output DEMs

	Nominal resolution (m)	Relative vertical accuracy (m)
Spaceborne photogrammetric		
Terra ASTER	30	20
SPOT5	30	10
IKONOS	2	~1.5
HRSC	~50	~20
HiRISE	1	~0.2
Spaceborne IfSAR		
SRTM C-band (11/02/2000)	90	10
SRTM X-Band (11/02/2000)	30	6
ESR Tandem (Oct 1995–June 1996)	25	20
TerraSAR-X	12	<2
ERS/ASAR Repeat Pass	25	20
Airborne		
IfSAR (NEXTMap)	1–5	?–1
LiDAR	<2	<0.25
Other		
MOLA	~460 (DEM)	0.38 (point value)

used to construct DEMs with resolutions of ~50 m (Heipke *et al*., 2007) and ~1 m (Kirk *et al*., 2007), respectively.

There has been niche use of radar imagery within geomorphology. For example, Vencatasawmy *et al*. (1998) took advantage of the side-looking geometry to exploit the enhancement of topography for geomorphological mapping, while the longer wavelength and active sensor means that its all-weather, day/night imaging capabilities make it a suitable for deployment over any region. However, the development of IfSAR capabilities (Rosen *et al*., 2000) has seen extensive application in both the generation of DEMs (eg, Muller *et al*., 1996) and the monitoring of ground motion and ground subsidence (eg, Cabral-Cano *et al*., 2008). This has been through the application of the ERS Tandem Mission archive (eg, Muller *et al*., 1996) and, more recently, through repeat-pass ERS-2 and ENVISAT ASAR data. There has also been some limited experimentation with ERS-2/ASAR tandem data (Kwoun and Lu, 2005), but differences in the carrier frequency make processing difficult. Spaceborne single-pass interferometric products are currently restricted to SRTM (Rabus *et al*., 2003), an 11-day NASA Shuttle mission dedicated to the production of a global DEM from 56°S to 60°N at a subsampled 90 m spatial resolution (although Grohmann and Steiner (2008) use omnidirectional kriging to increase the spatial resolution to ~50 m), with nominal 30 m resolution data available for the USA and Australia. Geoscience Australia, CSIRO and the Australian National University are currently enhancing the SRTM DEM by removing noise and vegetation effects. The SRTM actually comprised two IfSAR systems; in addition to the NASA C-band system, the German and Italian space agencies deployed an X-band system. This has been used to produce a second, independent, DEM (http://eoweb.dlr.de) with higher vertical accuracies, but reduced ground coverage. In addition, the shorter wavelengths of the C-band radar mean that in vegetated regions there is less penetration of foliage and therefore true ground elevation may not be achieved.

A recent and exciting development is the launch of TerraSAR-X, an X-band radar sensor from the German Space Agency and Infoterra. In spotlight mode, this offers up to 1 m spatial resolution data and was successfully deployed over Tewkesbury, UK (25 July 2007), during a period of severe flooding in order to assess bank-full discharge of the River Severn (Zwenzner and Voigt, 2008). A near-identical satellite (TanDEM-X) is scheduled for launch in 2009 and will orbit between 500 m and 2 km from TerraSAR-X (Palmann *et al*., 2008). This will allow single-pass interferometry, and the creation of DEMs with a spatial resolution of 12 m and a vertical accuracy of <2 m.

Other recent advances in sensors that have been utilized by geomorphologists include the development of microsatellites. The Disaster Monitoring Constellation (DMC) is a multination constellation of six satellites providing daily global coverage at a nominal spatial resolution of 32 m in Landsat compatible bands. Notably it can deliver 600x600 km imagery (http://www.dmcii.com) which is ideally suited to monitoring geomorphic environments (eg, Priestnall and Aplin, 2006). Similarly, the recently launched RapidEye (http://www.rapideye.de) is a constellation of five satellites also offering global coverage at a 5 m spatial resolution.

2 Airborne systems

In terms of primary output data, most of these systems are identical to satellite based sensors. However the lower altitude at which they are deployed allows much higher spatial resolutions. Stereo photography remains the primary source of data collected from the air, with the commercial deployment of metric digital aerial cameras (eg, Z/I Imaging Digital Mapping Camera) allowing the co-collection of 4-band VNIR with stereo photography. Other sensors are commonly flown, including multispectral, hyperspectral, LiDAR and radar systems. As an example, the CASI instrument measures reflected sunlight in a 545 nm spectral range configured for VNIR wavelengths in 96 spectral bands (eg, Deronde *et al*., 2008). The HyMap™ scanner records spectra from 420 to 2480 nm in 128 wavebands, with additional full width half maximum (FWHM) bands of 15 and 20 nm for the 420–1803 nm range and the 1949–2480 nm range, respectively (Cocks *et al*., 1998).

Passive airborne systems, such as gamma-ray spectrometry (radiometrics) and aeromagnetics (Brodie, 2002) and active systems, especially airborne electromagnetics (AEM; Lane, 2002), have been adopted from the mineral exploration industry by geomorphologists (eg, Wilford, 2009). Radiometrics provide information about the composition of materials in the upper 50 cm of the Earth's surface (Wilford, 2002), while aeromagnetics, properly processed, can provide images of subsurface features such as buried channels. AEM data, depending on the type of sensor, can provide a 3D image of conductivity to as deep as 100 m; properly constrained with drill hole data these can be converted to images of the 3D distribution of, for example, different lithologies in an alluvial sequence, or the base of an alluvial sequence (eg, Figure 3 in Kernich *et al*., 2009).

Perhaps the technology that has had the greatest impact upon terrain modelling has been the utilization of airborne laser scanning (ALS) and terrestrial laser scanning (TLS; the ground-based counterpart). These are commonly pulsed systems (Baltsavias, 1999) that record a range and intensity (often for multiple returns of the same pulse), generating millions of 3D point measurements or 'point clouds'. Point clouds can then be manipulated directly or interpolated to a grid based DEM. A variety of techniques have been developed for postprocessing point clouds; the most pertinent for geomorphologists include the removal of 'surface clutter' in order to retrieve the actual ground surface (Sithole and Vosselman, 2004). This involves the removal of 'early returns' from vegetation leaving only the 'late returns' that are from the ground surface. Interestingly, this also provides information about vegetation height. More novel uses of LiDAR include the generation of a DEM of the current visible surface and then the extraction of ground control points for photogrammetric processing (Barrand *et al*., 2009). This allows the exploitation of historic photographic archives for environmental modelling.

Intermap remains the primary contractor for the collection of airborne single-pass interferometric data, and has notably completed the production of DEMs for western Europe. Their current Star 5i sensor allows the creation of <1 m spatial resolution DEMs, although early products were restricted to ~5 m.

Finally, very high spatial resolution imagery can be collected through the use of close-range technologies. This has traditionally been acquired through the use of low-level airborne or heliborne surveys, although high deployment costs have led both to the use of terrestrial imagery (eg, Gilvear and Bryant, 2003) and to the development of innovative platforms, such as kites (Smith *et al*., 2009), UAVs (Lejot *et al*., 2007) and blimps (Fotinopoulos, 2004). These are relatively inexpensive and allow very low costs for repeat surveys. Primary data acquisition is usually stereo photography and, given weight constraints of the platform, non-metric commercial off-the-shelf cameras are normally deployed. Imagery obtained in such a manner is able to take advantage of digital photogrammetric software and recent advances in the processing of non-metric imagery (Chandler *et al*., 2005).

III Application to geomorphic research

Remote sensing techniques provide fresh insights in geomorphology in several ways (see Higgitt and Warburton, 1999; Slaymaker, 2001):

- new applications for geomorphology (eg, Mullen and Kellett, 2007);
- new and improved accuracy of measurement (eg, Hodge *et al*., 2009);
- new data that allow investigation of ideas that were previously untestable (eg, Hynek and Phillips, 2003);
- development of data processing capability (eg, Chandler *et al*., 2005);
- imaging of remote areas (eg, Hättestrand and Clark, 2006);
- advanced technologies such as AEM and radiometrics provide information about depth and composition (eg, Wilford, 2009).

When using remotely sensed images for geomorphic studies it is important to consider the aims of the study, and which remote sensing platforms will provide the most appropriate information, particularly in relation to the scale of the study (Pain, 2005; Hengl, 2006). It is also clear that real progress in the use of remote sensing in geomorphology will only be achieved by careful field data collection and field checking to confirm, or constrain, the results obtained from remotely sensed data. Such field checking ranges from regional observations of landforms and regolith to detailed drilling programmes.

Applications of remote sensing to geomorphic research range from simple interpretation of images to sophisticated image manipulation, modelling and integration with other data in a GIS.

1 Geomorphometric analysis

Geomorphometry is *the science of quantitative land-surface analysis* (Pike, 2000) and has a natural affinity with geomorphology in terms of the study of land surface morphology. Hengl *et al*. (2008) provide a review of principal concepts, data sources, analysis and application using current software. DEMs can be used to qualitatively and quantitatively investigate the landscape through the application of geomorphological mapping (performed in conjunction with satellite imagery) and the derivation of land surface parameters, respectively. These are discussed below.

The principles of recognizing patterns of landscapes on images, and the development of geomorphological mapping, have not changed since aerial photographs were used in the first half of the twentieth century. Pain (1985) summarized these principles in the context of Landsat MSS images and, although the number and resolution of remote sensing platforms and image data has increased markedly, the principles remain the same. The use of remotely sensed images, including those from Google Earth, is now commonplace in papers discussing regional geomorphology (Lisle, 2006). In addition, DEMs, either solely or in combination with image data, allow 3D image models to be produced, providing more powerful interpretation and visualization tools (eg, Buchroithner, 2002; Gazioglu *et al*., 2004). Smith and Clark (2005) and Hiller and Smith (2008) have reviewed methods for visualizing DEMs for geomorphological mapping, while Smith and Wise (2007) quantify the extent of random and systematic bias in using VNIR imagery for mapping linear landforms. Smith *et al*. (2006) compared a selection of national DEMs for geomorphological mapping.

There is a large number of studies that use images combined with DEMs. For example, Schneevoigt and Schrott (2006), using ASTER imagery and a DEM, show that alpine landforms can be detected using a hierarchical and multiscale classification. Some use simple image analysis techniques to enhance interpretations. Grosse *et al*. (2005) demonstrated the use of CORONA images (http://eros.usgs.gov/products/satellite/declass1.php) for mapping and interpreting the periglacial geomorphology of the NE Siberian coast. With a ground resolution of 2.5 m, the images they used discriminated a variety of periglacial forms. Using image density slicing they were also able to automatically map water bodies. Barnett *et al*. (2004) combined RADARSAT and Landsat ETM+ images with a DEM to map terrain attributes and then to predict surface materials, particularly sand and gravel. The large archive of historic imagery, in combination with a range of sensors, has necessitated innovative techniques for handling large data sets. Nikolakopoulos *et al*. (2007) used principal components of one Landsat MSS image, three Landsat TM images, two Landsat ETM images, and one ASTER image to map changes in the Alfios River channel in Greece over the period 1977–2000.

Quantitative analyses take advantage of the calculation of geomorphometric parameters from elevation. This has great power in process modelling as elevation can be used to derive information on gravity-driven processes: for example, gradient (gravitational force available for geomorphic work) and aspect (direction of 'work done' and subsequently used for calculations of insolation). Combinations of parameters can also be used to automate the process of landform identification through the application of *geometric signatures* (Pike, 2000). Further parameters are detailed by Hengl *et al*. (2008). Recent examples include Burberry *et al*. (2008) who used stream networks derived from DEMs as a proxy to determine the underlying tectonic landform organization, while Goldsmith (2006) tested the ability of artificial neural networks and decision trees for identifying gully systems in Spain. Saha and Munro-Stasiuk (2008) have applied object-based classifiers to the automated identification of drumlins. Within aeolian geomorphology, both Potts *et al*. (2008) and Bubenzer and Bolten (2008) used SRTM data to quantify dune morphologies.

High-resolution aerial photography is also being used to extract morphometric parameters. Within fluvial environments, Carbonneau (2005) used high-resolution (3 cm and 10 cm) digital aerial photos to estimate grain size on river beds, while Carbonneau *et al*. (2006) used digital aerial imagery to map river bathymetry. Marcus and Fonstad (2008) provide a comprehensive review of the use of digital photography for mapping rivers.

2 Spectral modelling

The identification of surface materials and geochemistry is carried out using spectral reflectance (Clark, 1999) in different bands. With an increasing number of sensors, many of which obtain data in several bands, the use of spectral reflectance has become much more sophisticated, and also more accurate. The Hyperion sensor, with 220 bands, has been used to successfully identify landforms and surface materials (Waldhoff *et al*., 2008). It is especially useful when combined with laboratory reflectance spectra of rocks (Sgavetti *et al*., 2006). When spectral data are combined with radiometrics, geomorphologists have a set of very powerful tools for identifying surface materials, even in areas of vegetation cover. Data from remote sensing can then be combined with field data to develop a set of decision rules that can be used to automate mapping of landforms and, to some extent, the underlying regolith (Pain, 2008).

Examples of the use of multi/hyperspectral imaging in geomorphology are extensive and the applications below are by no means comprehensive, but illustrate how techniques and data have been utilized. White and Eckardt (2006) used MODIS imagery to map carbonate distribution over large areas. When compared with estimates from Landsat ETM+ data this showed reasonable agreement, and there was good agreement with estimates from laboratory analysis of field samples. The results suggested that palaeolake levels with their surficial carbonate deposits can be mapped from MODIS imagery. White *et al*. (2007) used spectral mixture modelling of Landsat ETM+ imagery, supplemented with laboratory reflectance spectroscopy of field samples, to map the provenance of the Namib sand dunes and thereby infer the source and mixing regions. Mathieu *et al*. (2007) applied the spectral indicators of soil erosion to SPOT-HRV images to produce regional maps of soil degradation in central Chile, while Ben-Dor *et al*. (2006) used HyMap airborne hyperspectral imagery to map rubification of surface soils on sand dunes.

The application of radiometric techniques developed from mineral exploitation has been less extensive to date, but this is a growing field. Pickup and Marks (2000; 2001) used soil characteristics (derived from radiometrics) and landform properties (derived from a DEM) to assess erosion processes in the tablelands of New South Wales, and the Todd River area of central Australia. Wilford and Minty (2006) discuss the use of radiometrics for soil mapping, and point to the development of techniques using radiometrics and DEMs, with field checking, to develop weathering indices for land surfaces. Rawlins *et al*. (2007) provide a further example from eastern England, pointing out that soil parent materials can be identified from radiometric data. Lahti and Jones (2003) used radiometrics to demonstrate the movement of materials particularly in streams in England and Germany.

IV Geographic information

Changes in the wider geographic information community are also having profound impacts upon geomorphological research. The impact of US federally collected data remaining within the public domain cannot be underestimated, but it is noteworthy that other nations are also releasing their GI data free from charge, even if they remain under copyright (eg, Australia, Ireland, Canada). Acquisition of geospatial data is expensive, where, for example, an airborne geophysical survey can cost in excess of AUS\$500,000 for ~16,500 km^2. Where funded by public monies, many organizations make these data available for the cost of transfer, which for internet download is often free.

In a similar vein, many users have realized the problems in using proprietary data formats for storing their data and the Open Geospatial Consortium (OGC; http://www.

opengeospatial.org) has developed a variety of geospatial standards which are now extensively supported.

Finally, digital globes (eg, NASA Worldwind, GoogleEarth) have revolutionized the way in which research is carried out through access to imagery that would otherwise remain uneconomic to acquire. This has enabled pre-fieldwork reconnaissance, field mapping (Dykes, 2008) and accuracy assessment (Thenkabail *et al*., 2006). The distributed nature of digital mapping resources, and the establishment of geospatial web services, has meant that the distribution of data and the results of research can now be made widely available. For example, the Integrated CEOS European Data Server (http://iceds.ge.ucl.ac.uk) uses OGC standards to stream data to end-users within an open source web platform, while the Geodata portal at Kings College London (http://www.kcl.ac.uk/schools/sspp/geography/research/emm/geodata) distributes data for viewing within Google Earth using the OGC KML data format. Perhaps the earliest success in operation as a data portal is the Global Land Cover Facility (http://www.landcover.org) at the University of Maryland, which has now diversified in to a wider range of spatial data sets. Another example is the Open Topography Portal (http://www.opentopography.org/index.php), which distributes LiDAR images for parts of California also using the KML format, as well as linking to the original data.

V Conclusions

This paper has provided a brief overview of the application of remote sensing to geomorphology, placing advances in the last 10 years within the context of change since the review by Millington and Townshend (1987). This period is characterized by a proliferation of multispectral data from new sensors, driven by both national governments and commercial businesses, with a general trend towards providing data with higher spatial, spectral or temporal resolutions. Yet remote sensing can only find utility within geomorphology where it is able to meet the demands of geomorphologists. Figure 1 demonstrates that the real beneficiaries of advances in remote sensing have been in aeolian landform monitoring and small catchment monitoring (although the scope of the applications listed is limited). In addition to information on landform distribution and surface composition, remote sensing is now delivering data on land surface elevation and subsurface characterization, at increasingly higher spectral and spatial resolutions. This now goes some considerable way to meeting requirements for landform description/classification, process characterization and the exploration of linkages between landforms and processes. Certainly there is a much greater emphasis on anthropogenic influences upon the landscape which can largely be met within current systems. Multiscale investigations present a more complex challenge in terms of data acquisition (potentially over large areas) at high spatial and temporal resolutions, with the potential addition of hyperspectral data. This is the real vision of a truly multidimensional 'digital Earth' and one that requires a paradigm shift in the way that data is analysed.

In academia, there has been notable success in the use of Landsat ETM+ and Terra ASTER due to the functional multispectral wavelengths, reasonable spatial resolutions and, in the case of ASTER, elevation data, as well as the favourable policy on data redistribution. The widespread proliferation of moderate and high-resolution elevation data is perhaps the single largest change in applications of remote sensing in geomorphology. This is exemplified with the release of near-global SRTM data in 2004. As this data falls within the public domain, some researchers have focused upon reprocessing it into new products. Most notable are a void-filled data set from CGIAR-CSI (http://srtm.csi.cgiar.org) and the USGS HydroSHEDS (http://hydrosheds.cr.usgs.gov), developed for hydrological applications. Numerous sensors now offer DEM generation (eg, SPOT5, ASTER, ERS-Tandem) and these form a integral part of geomorphological investigations. It is worthy to note that these developments have been *preceded* by work in interplanetary remote sensing. The global DEM of Mars, produced from MOLA data, was released in 2003, while HRSC and HiRISE are producing high-resolution DEMs and imagery. HiRISE remains the highest spatial resolution (30 cm) non-military sensor orbiting any planet.

The use of airborne data remains high, with elevation products from LiDAR and IfSAR in great demand. The move away from analogue aerial cameras to push-broom digital aerial cameras is beginning to occur, with the dual acquisition of stereo and multispectral data that can be integrated back in to traditional photogrammetric workflows. Radiometric and AEM data are also being used to a greater extent and their application should spread more widely within geomorphology as data are acquired and become available at cost of transfer.

Future missions are likely to see 'more of the same'. While higher spatial resolutions are of great interest, they often do not provide the areal coverage or imaging conditions required for particular studies. Higher-resolution data also require great storage and computing capacity – a LiDAR survey can contain several gigabytes of data. The future launch of WorldView-2, GeoEye-2 and GMES Sentinel-2 will continue this general trend. Perhaps the most exciting development will be the launch of TanDEM-X to create a formation of two SAR satellites that will be able to perform single-pass interferometry for the generation of ~12 m DEMs. Of equal interest will be the continued deployment of low-cost satellite constellations, in the form of DMC and RapidEye, for continuous Earth surface monitoring. This is important for sub-50 m spatial resolution multispectral monitoring of the environment, particularly in rapid response situations such as natural hazard mitigation.

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