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Geovisualisation

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Synopsis (50-100 words)

Geovisualisation, the depiction of spatial data, is key to facilitating the generation of observational datasets through which Earth surface and solid Earth processes may be understood. This chapter focuses upon the visualisation of terrain morphology using satellite imagery and DEMs, where manual interpretation remains prevalent in the study of geomorphic processes. Techniques to enhance satellite images and DEMs in order to improve landform identification as part of the manual mapping process are presented. Visual interaction with spatial data is an important part of exploring and understanding geomorphological datasets and a variety of methods ranging from simple overlay, panning and zooming are discussed, along with 2.5D, 3D and temporal analyses. Visualisation outputs are outlined in the final section, which focuses on static and interactive methods of dissemination. Geomorphological mapping legends and the cartographic principles for map design are introduced, followed by details of dynamic webmap systems that allow a greater immersive use by end users, as well as the dissemination of data.

1 Introduction

Geoscientists aim to develop an understanding of the processes that create landforms, and in order to study landforms must be able to visually perceive them. So accurate, detailed and reliable visualisation is arguably of primary importance to the geomorphological study of processes shaping the Earth and other planetary landscapes. In geomorphology, the shape of the land is fundamental so, whilst other complementary data exist, elevation data are central to geovisualisation. Geovisualisation relates to topics covered in other chapters in this volume particularly remote sensing (XR: 3.1), digital terrain modelling (XR: 3.9), geomorphometry (XR: 3.10) and spatial analysis/geocomputation (XR: 3.14). Extensive and complex image processing techniques are applied in these areas, but many of these do not relate to visual display, which is the focus of this chapter. For simplicity, although geovisualisation is used more widely, terrain is used to illustrate geovisualisation.

The scope of this chapter includes focusing upon visual processing, visual interaction and visual outputs, all of which form part of the visual “depiction” of terrain. Much of this focus is related to geomorphological mapping, often a formal outcome of geovisualisation. Section 2 provides background context in terms of a historical perspective, formal definitions of geovisualisation, and an outline of emergent technologies and applications. Section 3 explicitly deals with Visual Processing and the optimisation of imagery for landform visualisation. Section 4 introduces the mechanics of various methods by which a user can interact with data once they have been

prepared for viewing. Finally, Section 5 discusses the dissemination of data in both traditional paper and electronic formats, highlighting various visualisation products. Terminology concerning geomorphology and elevation data are explained within the text and also collected together in a glossary. More detailed definitions are provided by Pike et al (2008).

This introduction starts by placing geovisualisation into its historical context, then focuses on visualisation for geomorphology where recent work is driven by the availability of digital datasets. The relationship of geomorphology to geovisualisation through geospatial analysis is then discussed and the term geovisualisation defined, leading onto an outline description of the uses of geovisualisation and a framework within which they can be categorised. Finally, the scope of the chapter is stated.

2 Background

2.1 Historical Context

The visual interpretation of data and conceptual ideas has been a key aspect of human understanding (e.g. Kraak and Ormeling, 2010). For spatial data, those where location is of importance, maps have been commonly created to assist in interpretation. Figure 1a illustrates the utility of creating maps for the investigation of geomorphic processes by displaying the distribution of glacial landforms and their composition (indicated by the symbol fill colour), something that is difficult to convey using vertical (Figure 1b) or oblique (Figure 1c) aerial photos. Alongside maps, alternative portrayals of spatial data have been routinely used (e.g. Kraak and Ormeling, 2010; Bonham-Carter, 1994): these include field sketches (Figure 2) and conceptual diagrams (Figure 3), vertical/oblique aerial photos (Figure 1b/c), satellite imagery, digital elevation models and augmented reality (e.g. Reitmayr et al, 2005).

Early geomorphological maps were often produced for military and engineering purposes and designed for use in the field (Klimaszewski, 1982). With the onset of a morphological view of landscapes and the description of their physiography at the turn of the 20th century, landform analysis and morphological description became new purposes for geomorphological maps (e.g. Passarge, 1912; Passarge, 1914). From this standpoint maps were more than just a medium for visualisation but represented a research tool for landscape analysis providing a generalised inventory of landforms, surface structures, geomorphological processes, surface and subsurface materials, and genetic information. The applications of geomorphological maps range from simple descriptions of a field site, for example accompanying a journal publication or construction site report, to land system analyses (Bennett et al., 2010), land surveys, land management or natural hazard assessment (Brunsden et al., 1975, Seijmonsbergen & de Graaff, 2006)

Maps remained the fundamental geomorphological output through to the 1980s as they provided both 2D visualisation and an effective data storage paradigm for spatial data. Geomorphological mapping subsequently declined due to a preoccupation with cartographic symbolisation and a move to field scale experimentation. Since the 1990s widely available remotely sensed data, progress in computing power, and the improvement of information systems (e.g. Wessel & Smith, 1998; ESRI, 2003) have permitted the combination of field scale and regional approaches, causing a resurgence in mapping. In particular the emergence of the GIS (Geographic Information System) through the wider field of geomatics has provided a digital tool through which disparate datasets

can be stored, manipulated, analysed and communicated. This provides a powerful methodology to combine diverse data such as total stations, GPS, satellite imagery, postcodes and historic sources. Specifically, GIS can be used to prevent data overload, facilitating the clear, carefully constructed presentation required for interpretation, analysis and higher-level use of the data

Historically geovisualisation has been a paper-based analogue technique, however it is now the routine collection and widespread availability of large digital datasets that is driving much analytical work facilitated by computer-based geovisualisation. Such large datasets are most often generated by remote sensing of various kinds; Smith and Pain (2009) review currently available datasets. In terms of data volume, satellite imagery remains the single most important product, although the balance between spectral resolution, spatial resolution, and temporal resolution can be problematic. However, in terms of impact upon geomorphology, the generation of digital elevation models (DEMs) (see XR: 3.9) has arguably had the largest effect. This is profound because a variety of elevation data can be synthesised into a DEM and, once in raster format, image processing methodologies, common in geovisualisation, can be applied. Contemporary mapping is therefore computer based, reliant upon the input of digital datasets, with analysis and output performed using GIS.

2.2 Geomorphology and Geovisualisation

Geovisualisation is much utilized in geomorphology for the exploration and analysis of spatio-temporal data. Whilst a spatial framework is not a requirement for geomorphological study (e.g. Smith and McClung, 1997), it is natural in many studies to use “space” as the organising paradigm (e.g. Benetti et al, 2010). A better understanding of many geomorphic phenomena can therefore be gained through the recording (i.e. ‘mapping’) and analysis of their spatial distribution. In the past the observed distribution and form (i.e. morphology) would typically have been communicated using a geomorphological map (e.g. Rose and Smith, 2008).

The term “geovisualisation” is a contraction of geographic visualisation. This was first mooted by MacEachren et al (2004), who defined geovisualisation as a “process for leveraging ... data resources to meet scientific and societal needs and a research field that develops visual methods and tools to support a wide array of geospatial data applications.” This definition extends geovisualisation beyond simply communication using the presentation of an image or images. The definition proposes that the term “visualisation” include four primary functions (Figure 4): i) ‘exploration’ of datasets e.g. in order to find landforms ii) ‘analysis’ e.g. of patterns and relationships between the landforms iii) ‘synthesis’ e.g. generating an overview and understanding of the origin of the landforms and iv) ‘presentation’ of the findings. Within this definition, geovisualisation incorporates a wide gamut of activities and capabilities. In contrast, Kraak (2008) suggested that “geovisualisation” was seeing inflation as a term: namely, that geovisualisation was being used increasingly widely and indiscriminately, becoming equated with “mapping”, and therefore increasingly less useful as a term. So, he favours the use of the term “geovisual analytics” (Thomas & Cook, 2005; Andrienko et al 2007) for the range of activities in and around the geovisualisation cube, implicitly retaining a more focused definition of “geovisualisation”. Discussion exists about the terminology surrounding geographic visualisation, yet, at its simplest, geovisualisation is simply a synthesis of the long-developed visual communication of cartography with current digital analytical technologies, principally GIS. Indeed, it could be argued that in the past cartography was geovisualisation; that is, cartography embodied the sum of geovisual techniques that were possible before practical, pervasive desktop computing. The introduction of

computer technologies in the 1960s, however, saw a split in the discipline of geographic visualisation with users either focused principally upon i) design and communication or ii) data handling. The former we now think of as cartography, whilst the latter became geographic information science. The meaning of the term geovisualisation is therefore debated, but in its widest, intuitive, sense it is '*the visual depiction of spatial data*'. It is a convenient term to employ within geomorphology, and is used here with this latter broad meaning.

2.3 Applications and Emergent Technologies

Some applications of geovisualisation are depicted in Figure 4, with the axes of the cube illustrating the task being performed, the user doing the task, and the degree of interaction with the data being visualised. Within this, MacEachren et al's (2004) four functions (Section 2.2) move sequentially from highly interactive exploration of the data by specialists in order to generate basic observational knowledge, to presenting synthesised information to the public involving little interaction with the data. "Knowledge construction" at the start of this sequence requires a specialist user with a high degree of interaction and can be considered a research-intensive application. At the opposite end of the spectrum, "information sharing" generally requires lower levels of interaction by non-specialists and is an application for the public and decision makers. This latter area is now an important aspect of research as funding bodies are aware of their accountability and therefore desire further downstream application, as well as interaction with the general public or, more generally, "public relations".

Two trends not well represented by the four functions proposed within the geovisualisation cube are the growth in both public interaction with data and data distribution to the widest possible audience. The latter facilitates the former, and with both specialists and the public exploring data, the face of the cube representing high levels of interaction is becoming increasingly occupied. Specifically, there are 3 requirements for this occupation to be achieved:

- freely or easily available data
- non-proprietary or 'open' formats for geospatial data
- free or easily available software or simple tools to download, visualise and analyse data

The public release of data is not new (e.g. SYNAPS: VanWykhouse, 1973), but there has been an increasing political pressure to do so. In the USA the National Geophysical Data Center (<http://www.ngdc.noaa.gov/>) makes data publically available and it is a requirement of funding that data be released. The UK government has released significant quantities of data (<http://data.gov.uk>), and UK research councils also require scientists to place their data in repositories. Data sharing and archival requires a move away from proprietary data formats and this has been achieved through the development of industry standard, open, formats (e.g. KML) and openly specified proprietary formats (e.g. the shapefile format; ESRI, 2003).

The ability to select base data and easily overlay specialist datasets is fundamental across a spectrum of activities, ranging from the development to the use of applications. For example, Generic Mapping Tools (Wessel & Smith, 1998), GRASS and QGIS allow scripting to enable advanced users to create wider dynamic access to data. The Seamount Catalog (<http://earthref.org/SBN/>; Koppers *et al*, 2010) exemplifies a scripted front end to geospatial data. For both technical and non-specialist users, GeoMapApp (<http://www.geomapapp.org/>; Carbotte *et al*, 2004) is a free, easy to use software package that contains datasets, displays (e.g. maps and profiles) and overlays data and allows users to import new data. GoogleEarth performs similar

tasks in an accessible way, encouraging map-making by the public at large. The public use of geovisualisation itself is no better displayed than in the culture of “mashups” (e.g. Wood et al, 2007), and by the ease of use of a site that allows anyone to make maps (e.g. <https://arcgis.com>). See Section 5 for more details on data dissemination and visualisation products.

3 Visual Processing

Geomorphologists are interested in the geovisualisation of spatial data in order to understand the Earth’s surface. Specifically, to form their observational data set, they identify and classify landforms pertinent to their field of study in order to later analyse them. The observational data are representations of the location and extent of landforms, and the work of their creation may be termed ‘terrain modelling’. An intermediate output of terrain modelling may be an enhanced data layer for further visual inspection or data analysis. Ultimate outputs are typically maps for distribution, analysis and archival. Although researchers may conduct fieldwork for the mapping of landforms, this section will only consider terrain modelling as applied to VNIR (visible and near infra-red) and DEM data. Specifically, the concepts of ‘topographic signal’ (Hillier & Smith, 2008) and ‘detectability’ (Smith and Wise, 2007) are introduced. These are then used to inform processing techniques for satellite imagery and DEMs that enhance the visibility of specific landforms by increasing the ratio of (topographic) signal-to-noise of an image. The section concludes with recommendations for enhancement and cautions about limitations in geomorphological mapping using digital data.

The process of landform identification can be performed using manual or automated/semi-automated techniques. Manual mapping techniques require a skilled interpreter to identify and outline landforms of interest. Skill, how well landforms are identified, is based upon both the expertise and experience of the interpreter and is closely related to the more generic technique of image interpretation (Colwell, 1983; XR: 3.2, 3.11) that has been extensively developed for analogue aerial photos. The process is qualitative and relies upon the development of ordered relationships between features in an image using complex visual heuristics in order to identify object types. Whilst primarily focused upon panchromatic aerial photos, the introduction of colour, multi-spectral, thermal and radar data, for example, has led to the extension of these techniques in to new domains. However the basic process remains the same: that is, the identification of landforms via the assessment of shape, size, tone, texture, shadow, pattern, location and association. For further details on this process readers are directed to both chapters in this volume (XR: 3.2, 3.11) and general textbooks on remote sensing (e.g. Lillesand et al, 2008; Campbell, 2007; Gibson and Power, 2000).

Automated and semi-automated mapping techniques use a variety of algorithmic approaches to identify landforms (e.g. Hillier & Watts, 2004; Van Asselen & Seijmonsbergen, 2006; Seijmonsbergen et al, 2011). Such approaches have the benefit of being numerical, repeatable and not reliant upon an individual interpreter or systematic variation during processing. Any inherent biases tend to originate from the ultimately subjective calibration underpinning the method. A significant number of these approaches are primarily statistical, having been developed from clustering methods used more generally in remote sensing (XR: 3.14). The increasing availability of DEMs, however, has allowed the incorporation of elevation and derived land surface parameters; this latter topic falls within area of geomorphometry (XR: 3.10). The wealth of remotely sensed data now available has opened considerable opportunities for developing the processing of

extensive datasets, as well as integrating them in to new types of analyses. Camargo et al (2009), for example, integrate reflectance data in to geomorphometric object-based analyses, and this is likely to become common as devices such as hyper-spectral satellites become operational. Further insights can be gained through the integration of sub-surface data from active and passive sensors. At sea, the sub-surface structure has been commonly probed using sound (e.g. seismic reflection), electrical (e.g. resistivity), magnetic and gravity fields; see Jones (1999) for further detail. On land, passive airborne systems, such as aeromagnetics (detecting subsurface magnetic features), and active systems, such as airborne electromagnetics (3D conductivity), provide subsurface data (Smith and Pain, 2009). The use of automated and semi-automated techniques that integrate a variety of datasets is therefore expected to become increasingly prominent.

Automated and semi-automated mapping techniques are important tools that can be utilised by geomorphologists, however manual mapping remains the most prevalent technique for recording the shape and distribution of landforms. Automated landform identification techniques are therefore not considered any further here.

3.1 Detection of Landforms

Manual mapping requires the visual detection of individual landforms, then recording their morphology on to some kind of basemap. Detection can take place using traditional VNIR imagery, whether that is aerial photography or satellite imagery, as well as imagery from other parts of the electromagnetic spectrum or DEMs. Smith & Wise (2007) outline the concept of *detectability*; that is, the ability for an interpreter to accurately identify the true dimensions of a feature of interest. This is dependent upon the *data source*, *image pre-processing* and the *skill of the interpreter*. Interpreter skill is difficult to quantify and variable between individuals, but there are procedures that can be implemented to minimise the limitations of interpreters. Fundamentally, however, the detectability of a landform will be dependent upon the characteristics of each sensor and how well that sensor performs in the physical conditions prevalent at the time of data capture. The following three characteristics therefore combine to affect landform detectability and should be considered by an interpreter prior to selecting data:

1. **Relative size** (Figure 5): the minimum resolvable size of a landform that is visible on an image is a function of the spatial resolution of that image. Data resolution must be high enough, or the landform large enough, that it contains sufficient pixels to be recognisable. Small features may be under-represented in any population, and where spatial clustering of small landforms exists systematic errors may consequently result.
2. **Azimuth Biasing** (Figure 6, Animation): angle along the length of elongated landforms (e.g. drumlins). The orientation of elongated features causes their appearance to differ dependant on their angle with respect to an illumination source if presented or imaged this way (satellite imagery, relief shading). This is far more pronounced for more elongate landforms (Smith & Clark, 2005).
3. **Landform Signal Strength** (Figure 7): the amount of tonal and textural information that is available to visually distinguish individual landforms, also termed 'topographic signal' (Hillier & Smith, 2008). For DEMs the signal is a component of the measured heights, relating to the landforms of interest (see Section 3.3.1). For VNIR imagery, topography is inferred from: (i) associations between landforms and land cover (e.g. Punkari, 1982) and (ii) tonal and textural information from shadows (Slaney, 1981), particularly where solar elevations are low. Synthetic

aperture radar (SAR) systems use an oblique (rather than nadir) viewing geometry (Ford, 1984; Vencatasawmy, et al, 1998) which enhances topography.

The minimum resolvable platform size of detectable landforms can only be reduced by increasing the spatial resolution of data (imagery or DEM) being used (Smith et al, 2006). Whilst this data may be available, there will almost certainly be a trade off between financial cost and spatial coverage, and the objectives of a project may have to be tailored to the resources available (e.g. Punkari, 1982). For VNIR imagery, routine repeat coverage from moderate resolution sensors (e.g. Landsat) mitigates this somewhat as images at optimal illumination angles and azimuths may be available in the large archives of this imagery.

Azimuth biasing is perhaps the most significant problem for satellite imagery. Bias is minimised through the acquisition of imagery with a high illumination elevation (i.e. closer to overhead), however this minimises the landform signal strength so that features are not clearly observable (Figure 7). Smith & Wise (2007) recommend illumination azimuth to be $< 20^\circ$, however polar orbiting satellites operate with fixed overpass times which means that it is not possible to specify acquisition time at a site, although seasonal variations can be used to attain low angle sun if snow and cloud free scenes can be obtained. With a reduced ability to obtain ideal satellite imagery, ephemeral landforms are commensurately more difficult to monitor. If illumination elevation drives the selection of imagery and, as is commonly the case, it is not possible to control for illumination azimuth, interpreters should be aware of introducing systematic biases through the exclusion of suites of landforms. Azimuthal bias does not affect DEMs unless they are displayed using low-angle illumination for relief shading.

For both DEMs and satellite imagery it is possible to enhance the signal to make landforms more detectable, manual mapping easier, and thus hopefully the observational data sets created more complete.

3.2 Enhancement of Satellite Imagery

With the acquisition of appropriate satellite imagery, it is necessary to process or enhance the imagery to provide the best possible visualisation of landforms. Enhancement is largely based upon a sub-set of the standard image processing techniques, namely those applied in remote sensing (e.g. Lillesand et al, 2008; Mather, 2004) that have proven useful for geomorphological visualisation. Clark (1997) notes that brightness variations are most effectively detected by the eye and therefore recommends the use of images rendered in grey-scale ('panchromatic'); for multi-spectral imagery the interpreter should experiment with different 'bands', and the relative weight give to each band (i.e. 'band ratios'), in order to create an appropriate image for mapping. Standardised contrast enhancements such as a linear stretch, histogram stretch or standard deviation stretch should be utilised in order to maximise the visible contrast within the image. Convolution (kernel) filtering can also prove useful in highlighting detail with a high pass filter commonly used (Lillesand et al, 2008).

The work of Punkari (1982) illustrates how imagery outside the visible spectrum may be useful in identifying landforms. Inter-drumlin regions in his study contained greater moisture availability which impacted upon land cover, resulting in lower reflectance in VNIR bands, and thereby better differentiating drumlins. In a second example, Jansson and Glasser (2005) found false-colour

composites integrating near infra-red and thermal infra-red bands, in combination with relief shaded DEMs, most effective.

Whilst DEMs record elevation rather than reflectance, using the terminology of imagery they may be thought of as a single 'band' and therefore any of the techniques described above can be applied to them.

3.3 Enhancement of DEMs

DEMs directly record elevation and therefore landscape shape can be inferred from them. DEMs are treated differently from satellite imagery, although some aspects of processing are common. By default most image-processing software display DEMs as a greyscale image with a palette of shades representing height that linearly varies between the maximum and minimum heights in the dataset; a simple 'panchromatic' display (Figure 8). In such images small, low amplitude, features are not easily visible against larger-scale higher amplitude features typical in landscapes. It is therefore necessary to focus on the component of the landscape containing features of interest, enhancing the 'landform signal strength'.

3.3.1 Regional-Residual Separation

As an aid to better understanding of Earth surface processes, landforms can be divided into classes or categories, based on some similarity of form, or *a priori* knowledge that they relate to the physical process of interest. A class of features thought to relate to a process constitute a 'component' of a landscape or DEM. If H is elevation, the decomposition of a DEM into components may be expressed as $H_{DEM} = H_1 + H_2 + \dots + H_n$, where n is the number of components, H_{DEM} the observed elevation, and H_n the thickness of a component, which is a layer with a thickness greater than or equal to zero at every map location (x,y) in the DEM's grid. Summing the components recreates the terrain. 'Regional-Residual (Relief) Separation' (RRS) is the act of isolating landforms, ideally completely and uniquely, in to one component so that they may be studied independently. Wessel (1998) coined the term as applied to DEMs, and Hillier & Smith (2008) introduced it to sub-aerial geomorphology.

Figure 9 illustrates one RRS method by which two components, one containing 'drumlins' and the other 'hills' may be isolated from one another. Other examples of RRS include quantifying the large-scale subsidence trend across the oceans to understand how tectonic plates evolve (e.g. Sclater et al, 1975; Calcagno & Cazenave, 1993), isolating underwater volcanoes to better understand how the Earth melts (White, 1993; Hillier & Watts, 2007), removing trees and other surface features to 'decluster' DSMs and create DTMs for tasks such as flood modelling (e.g. Sithole, 2004; Mason *et al*, 2007), or archaeological prospecting (Hillier *et al*, 2007; Hesse, 2010). Note that components are not 'terrain units', areas of similar properties in a conventional geomorphological map.

By convention the 'regional' component contains features of a larger width-scale than the 'residual' components because, in older methods (e.g. Watts, 1976; McKenzie *et al*, 1980; Hillier & Smith, 2008), a trend representative of a region was calculated first and then subtracted to leave the 'residual'. Alternatively, it is possible to directly isolate (i.e. identifying and determining spatial limits for) all individual features of a certain type within landscapes (e.g. Hillier & Watts, 2004; Hillier, 2008) leaving the regional trend. But, the same naming convention is still used. The skill in

performing a successful regional-residual separation is always determining a property that makes the features you wish to isolate distinctively different.

The earliest regional-residual separations were manual (e.g. Menard, 1973; Sclater et al, 1975), so the quantitative distinction between the components is not known. Computationally, early methods used efficient 'frequency domain' filters (e.g. Watts & Daly, 1981, Casenave *et al*, 1986) to retain long wavelengths (λ), e.g. $400 < \lambda < 4000$ km, in the regional. Using the same mathematics, high-pass filters (Section 3.2) emphasise the small-scale residual; this relies upon the wavelengths present in different components not overlapping. 'Spectral overlap' is therefore a problem (Wessel, 1998).

Alternatively, 'normal' regional elevation can be estimated using 'linear combination' filters (e.g. the mean), usually implemented as a 'sliding window' or 'kernel' filter such as the boxcar (e.g. Watts, 1976; McKenzie *et al*, 1980, Wessel & Smith, 1998). However if normal elevations are rare, perhaps where there are many volcanoes and little remaining original seafloor, bias can occur underestimating heights and volumes in the residual (Smith, 1990). 'Robust' statistics such as the median and mode can mitigate this substantially (Smith, 1990, Crosby, 2006; Kim & Wessel, 2008), as can iterative statistical approaches (Marty & Cazenave, 1989; Wang et al, 2001).

These older techniques are good first approximations, and remain perfectly adequate solutions in some situations (e.g. Hillier & Smith, 2008). The main difficulties are listed below

- Spectral overlap between classes of landform (e.g. Wessel, 1998).
- Spatial overlap of landforms.
- High spatial density of smaller landform obscuring regional trend (e.g. Smith, 1990).
- Complex high-amplitude regional trends.
- Widely ranging shapes and sizes within a class of feature (e.g. seamounts, drumlins).

A number of complex algorithms have focussed upon overcoming these problems in order to create a regional (DSM) when de-cluttering LiDAR data (e.g. Sithole, 2004). For geomorphic features, several algorithms also exist that identify the smaller features directly (Hillier & Watts, 2004; Hillier, 2008). These seek to avoid the problems experienced by the older approaches above, and have the advantage that features are implicitly mapped during the separation but, like the de-cluttering algorithms, are somewhat task specific. Lastly, if the locations of features are known *a priori* this information may be used (e.g. Smith et al, 2009), but 'known' must be treated with caution.

Once a component is isolated through regional-residual separation it can be enhanced, parameterised (as in Section 3.3.2), displayed and the features mapped as with any other DEM. The possibility of distortions to morphology that may or may not arise during the RRS must be acknowledged, but if performed well the landforms of interest will be distinct.

3.3.2 Land Surface Parameters

In order to facilitate mapping, parameters derived from elevation as represented in a DEM are commonly calculated. Where they are physically based they are known as land surface parameters (LSPs). These may then be displayed separately (or in combination) for mapping and are described in more detail below.

Shading a landscape as if illuminated from a specified azimuth and elevation assuming a perfectly specular (i.e. mirror-like) reflector, or *relief shading*, is widely implemented in software and the most common DEM visualisation technique (Kraak and Ormeling, 2010). Relief shading, however, highlights a break-of-slope as seen from a particular direction which does not necessarily reflect the whole morphology and suffers from azimuth biasing (Section 3.1). Figure 6 illustrates the problem with a DEM illuminated parallel and orthogonal to the principle landform orientation, and with an animation where the illumination azimuth is rotated through 360° at 5° intervals; for the latter, landforms both appear/disappear and change shape. It is therefore common to utilise relief shaded images generated from multiple azimuths. An alternative solution is to use principal components analysis (PCA; Lillesand et al, 2008) to produce optimal combinations of relief shaded images (Smith and Clark, 2005). PCA is a statistical technique designed to reduce the dimensionality of data through the designation of new orthogonal axes along the line of maximum variance. Once resampled to the new co-ordinate system, the first output images contains more “information” than any single input image.

The above discussion illustrates that even if a DEM faithfully records a landscape, the method by which it is prepared for display can introduce bias. It is therefore preferable to use LSPs that are designed to have no azimuthal bias; additionally, if they are used numerically (rather than for display) they provide the basis for progress towards reproducible mapping methodologies

Slope, sometimes considered the “building block” of terrain (Evans, 1972; Olaya, 2008) as it controls the component of gravitational force available for geomorphic processes, is defined at a point as a plane tangential to the land surface. That plane has a steepness (gradient) and orientation (aspect) (XR: 3.10). Gradient is commonly used as an LSP for mapping as many landforms have steep sides, but users often find it unintuitive and require familiarisation. Greyscale display of gradient is best when flatter areas are light, giving an image similar to relief shading but without azimuth bias (Figure 10a). *Curvature* is a measure of the rate of change of gradient and may be quantified in three ways (Schmidt et al, 2003): profile, planform and tangential. Profile curvature measures downslope curvature (the derivative of gradient) and highlights breaks-of-slope (Figure 10b). It is therefore most appropriate for landform mapping, but like gradient some find it difficult to interpret and so familiarisation is often required.

Roughness, the variability of elevation of a topographic surface at a given scale, has also been used extensively as an LSP for landform characterisation (Figure 11a). For example, McKean and Roering (2004) separated landslide debris from different time periods based upon decreasing roughness as a result of subaerial erosion. The various ways roughness can be computed are reviewed by Grohmann et al (2011), who reduce them to three main approaches: ‘area ratio’, ‘vector dispersion’ and ‘standard deviation methods’. The first calculates the ratio between the area of a dipping surface and its area when projected onto a horizontal plane (Hobson, 1972), with values approaching one indicating flat surfaces. The second calculates vectors normal to local tangents to the land surface, then calculates how concentrated or dispersed these vectors are (Hobson, 1972; Guth, 2001; McKean and Roering, 2004). For flat terrain, vectors are near vertical, and dispersion is low. Finally, standard deviation calculations of elevation, slope and residual relief are commonly used.

Landforms may also be emphasised by computing local relative elevation as an LSP (e.g. Hiller et al, 2007), which makes local variations dominant. Smith and Clark (2005) refer to this as a local contrast stretch, applying a linear stretch across a user-specified kernel of the appropriate width

(Figure 11b), which assigns elevations a value according to their relative position between the lowest and highest point in the locality.

Yokoyama et al (2002) propose terrain “openness” as an LSP. Openness (or the opposite, “enclosure”) is calculated using line-of-sight methods that emphasise convexity and concavity in terrain, capturing the degree of geometric “dominance”. It utilises standard viewshed algorithms, but calculates these at nadir and zenith for eight compass directions. The parameter is sensitive to changes in local relief, where multi-scalar expressions of openness (i.e. distance) will have an impact. Conceptually it is related to measures of both roughness and curvature, although the interpretation is different.

3.4 Recommendations for Terrain Visualisation

A range of techniques designed to best enhance satellite imagery and DEMs for landform detection have been outlined in the previous sections. The selection of the most appropriate visualisation technique will depend upon the mapping task to be performed; however there are some approaches that can be recommended as generally applicable.

Simple panchromatic greyscale plotting of DEM data is rarely useful as a visualisation technique for landform mapping. It is therefore necessary to utilise techniques that are designed to highlight landforms of interest. Although appropriate RRS methods are not necessarily trivial to design, simple methods can be effective in highlighting individual landforms of interest, relegating all other aspects of terrain to “noise” (e.g. Hillier & Smith, 2008). An appropriate RRS to isolate the landforms of interest will always tend to improve the output of any subsequently applied technique.

The technique of relief shading highlights subtle topographic features well, is widely implemented in software, fast to compute, and very useful when appropriate care is taken to allow for azimuthal bias. Azimuthal bias from the artificial illumination source used alters the position of breaks-of-slope, thereby giving the impression of landforms changing shape or disappearing. The use of multiple relief shaded images at least partially mitigates this problem. This does not correct the problem, however, only making the interpreter aware of it. So, techniques that do not involve illumination are preferable. Computation of gradient and profile curvature are recommended even though interpretation of greyscale plots used to display these parameters may require experience. Openness and roughness also offer illumination-free visualisation methodologies that may be appropriate for certain applications. A local contrast stretch may enhance images displaying any of these parameters. Smith & Clark (2005) and Hillier & Smith (2008) review most of these methods, concluding that no single technique is ideally suited to terrain visualisation. Best practise for landform visualisation and mapping is therefore likely to involve the use of a bias-free technique, supplemented by relief shaded imagery.

4 Visual Interaction

Visual Processing, as introduced in the previous section, presented a selection of techniques for the *static* visualisation of terrain. That is, the outputs are fixed 2D entities, however it is often necessary to combine and interact dynamically with data in order to explore it more in more detail. This section introduces common techniques to dynamically interact with spatial data and then explores increasingly sophisticated methods for interacting with geomorphological data as 2D

planes and 2.5D surfaces, before outlining how surface data can complement true 3D volumetric data.

4.1 Display

Raster outputs of terrain are usually displayed and inspected upon a video display unit (VDU) using the red, green and blue (RGB) additive model of mixing colours (Figure 12; Lillesand et al, 2008). Given the sensitivity of the human eye limits colour perception to RGB, the colour cube allows the mixing of the three primary colours at different intensities to provide the full gamut of possible viewable colours. It is therefore possible to display up to three separate images of the same area at any one time by encoding the pixel values as a three-dimensional coordinate position within the colour cube. This is known as a *false colour composite* (unless it represents the actual object colour as perceived by the human eye in which case it is a *true colour composite*). The technique is widely used in remote sensing and, within geovisualisation, allows the interactive inspection of multiple terrain datasets.

Figure 13 presents an example of how a false colour composite can be used to interpret geomorphology; this combines topographic openness (green; 501x501 m kernel) and slope angle (red; 3x3 m kernel). Reddish colours represent high slope (and low openness) values and blueish colours represent high openness. A watershed (top left/light blue) is clearly depicted with drainage channels running away from it (red); below this are moraine ridges (centre left/light purple), gypsum sink holes (centre/red) beneath till and mass movement (centre/light red/yellow).

4.2 Digitisation and Overlay

The main output of visual processing is a raster dataset, or datasets, created using the techniques outlined above. These can then be interpreted by geomorphologists for the identification of individual landforms and the recording of their position and extent. The process is generically known as “digitisation” and can form a body of work for the production of geomorphological maps (e.g. Hughes et al, 2010) or inputs for further quantitative processing (e.g. Smith and Rose, 2009). Digitisation is the electronic creation of geographic coordinates, usually through a mouse click at the position identified on screen. When the coordinates are used individually (points) or combined together (lines or polygons), they are known as “feature types”, with each feature type forming a separate layer.

Layers can be stacked (e.g. overlain) and reordered, allowing the interpreter to interact with different data layers and visually inspect their interaction. This simple organisational framework provides a powerful paradigm through which geomorphologists can work digitally and is conceptually the same as overlaying tracing paper on an aerial photo and tracing the outlines of landforms. The geomorphologist can then move the layers with respect to one another, changing their order, as well as removing or adding layers. The process is non-destructive and can involve modifying other interactive features such as layer symbolisation. Raster layers (such as DEMs or satellite images) are typically rendered as opaque, obscuring any data they are overlaid on to; a simple solution is to switch layers on and off so that the interpreter can rapidly move between them, either manually or automatically at a prescribed frequency. Alternatively, users can operate a slider to move a new layer horizontally or vertically across the data viewer. Simultaneous viewing of a raster data grid and vector data is simpler as the vector data can simply be overlain. The

ability to manage large datasets and interact with them, allowing detailed inspection is an important, although simple, feature of a digital workflow.

The challenges in digital workflows come not through the use of technology, but in planning and organising the digitisation process. It is important to pre-determine the features that are of interest (e.g. Sahlin and Glasser, 2008), and group them thematically (e.g. fluvial, glacial, peri-glacial, mass movement). The choice of feature type used to represent the landform will depend upon the landform being digitised and the scale of mapping; it is important to remember that feature types are simplified categorizations (or abstractions) of reality, and that definitions change over time. Polygons approximate outlines of 2D features, or *area features*, such as drumlins or landslides. However, over larger areas lines and points can also be used to represent some area features. For example, regional scale mapping may represent drumlins as lines and landslides as points.

Further detail on the overarching rationale for geomorphological mapping is discussed by Dramis et al (2011), whilst Smith (2011) details the digital workflows involved.

4.3 2D to 2¹/₂D In Space

A simple way to interact with data is through activities such as zooming, panning, rotating, and performing simple contrast enhancements. There is a risk that these techniques become to seem trivial as a result of the ease with which the user is able to perform them. However, rudimentary visual exploration is an essential task. Google Earth, for example, provides an elegant interface for the navigation of a single set of imagery for anywhere on Earth; this is a remarkable achievement. Indeed the scale of their data licensing means that Google Earth is often not only the first data source queried, but the most up-to-date and highest spatial resolution (e.g. Dykes, 2008). Most commercial GI software support basic interactive visualisation, often augmented with 'aspatial' statistical output limited to summarising the whole dataset. Whilst somewhat restricted, these "global" measures can be used to explore features of individual datasets. For example, histograms of DEMs can highlight artefacts resulting from the conversion of contours (e.g. Smith, 1993; Wise, 2000). Wood (1993) introduces aspatial measures, but highlights the benefit of visualisation in identifying error in DEMs (Gousie and Smith, 2010).

Animations provide a powerful methodology for data visualisation by depicting *attribute change* to vector or raster data. Figure 6 demonstrates that effect of changing illumination azimuth when relief shading is used to display a DEM; in this instance each frame of the animation is rendered using a different illumination azimuth. Perhaps more commonly, temporal data can be animated where each frame represents a successive time 'slice'. Frames can progress at a fixed rate or be manipulated manually, for example using the "time slider" available in Google Earth where users can step through the historical archive of satellite imagery and aerial photography. For DEMs, time-stages in a modelled landscape evolution could be similarly displayed. This type of functionality is now incorporated in to many desktop GIS software. For quantitative work, change analysis of time-series raster data can be performed through the calculation of difference between values for a grid cell at two times (e.g. Etzellmüller, 2000; Chen et al, 2004). TIMESAT (Jonsson and Eklundh, 2004) extends imagery analysis to multi-epoch data, and similar results are achievable in geomorphology.

The above discussion has focused upon the 2D manipulation of spatial data. DEMs form a special case as they are a 2D array representing the upper surface of a 3D volume, but are not 3D as they do not define a volume. They are also not 2D in the sense of a plane or map, so are sometimes referred to as 2.5D. A variety of GIS applications allow a user to navigate a 3D volume examining the DEM surface vertically and horizontally through rotation and panning (e.g. Jordan et al, 2009). Data can not only be viewed on traditional 2D screens, but also on 3D display systems allowing the user to interact with perspective views of the terrain, overlay aerial photos and satellite imagery from different time periods and add digitised vector linework which can subsequently be edited. This enables virtual field reconnaissance and is particularly important for remote or inaccessible sites. The penetration of Google Earth into the geomorphological community has enabled many users to become familiar with this method of navigation and the creation of 'flight paths' that can be automatically navigated or animated for 'fly-throughs' (Figure 14).

4.4 3D in Space

It is natural to move from 2.5D to full 3D visual interaction with data, either in terms of estimating volumes, or being displayed in conjunction with true 3D volumetric data (e.g. seismic reflection data). As noted above, DEMs do not provide volumetric data, however where it is possible to define a lower boundary through an understanding of a geomorphological basal surface (e.g. Sclater et al, 1975; White, 1993; Wessel, 1998; Hillier & Watts, 2004; Smith et al, 2009), volume can be estimated. In this context, volume is computed as the height or thickness between the lower and upper bounding surfaces of a landform. These calculations may be the only estimate of volume possible in a study, but uncertainty exists as the basal surface is always based on inference.

Where sub-surface data, and additional surface data, can be collected a DEM can be seen as just one dataset contributing to an understanding of a 3D volume. Airborne radiometric, magnetic and electromagnetic measurements of the sub-surface, for instance, could be integrated. Further datasets derived from laser scanning can give information about supra-surface features such as vegetation canopy structure (e.g. ECHIDNA) to, for example, estimate biomass (Lovell et al, 2003). Integrating such geophysical data with DEMs in order to understand geomorphic processes has been the focus of much recent work (e.g. Jordan et al, 2009; Johnson et al, 2006; Hillier *et al*, 2008). Processing and display to achieve insightful interrogation of 3D data is exemplified in tools for the oil industry for processing seismic reflection data and integrating this with other geospatial information such as well log measurements (e.g. GeoVisionary, GeoWall, ProMAX, GeoProbe, and KINGDOM). 3D visualisation packages integrating data such as outcrop sedimentary logs, strike-and-dip measurements, and horizon interpretations with photography draped over a LiDAR DEM have been developed for sub-aerial work (e.g. Fabuel Perez *et al*, 2010). These packages typically display one or many planar slices through a 3D volume, or render the 3D volume on to a screen. Visualisation of such data can be enhanced by true 3D display usually through the application of stereoscopy. A variety of systems are currently available, with the general popularity of 3D video films leading to the development of low cost home systems that utilise one of two main systems: *polarised* and *shutter-based*. In polarised systems, a single monitor can display polarised images which are interlaced on the screen. Through the use of polarised glasses, the human visual system assembles the display in to a 3D image. The use of interlacing effectively halves the resolution of the image, although some manufacturers use a twin monitor set up to mitigate this effect. Shutter based systems use glasses that are actively controlled by the host computer; this synchronises the use of a blocking shutter on each lens of the glasses with the display of left and right stereoscopic

images and can utilise the full resolution of the display. Projection systems (e.g. GeoWall) are better developed as twin projectors using polarised filters and screen allow very large images to be displayed at full resolution. We therefore see integration of surface, surface structure, and subsurface information as being integral to the future building of detailed models for a wide range of applications.

4.5 Virtual Globes

Virtual globes, or Earth browsers, and online maps have become a central part of the internet since the first release of NASA's World Wind (<http://worldwind.arc.nasa.gov>). High resolution seamless satellite imagery and DEM data changed the view and perception of the Earth within a few years, placing more public emphasis on geomorphology (Tooth, 2006). The geosciences community has embraced the use of virtual globes with emerging applications in many fields: from simple terrain inspection and feature mapping (Sato & Harp, 2009; Welsh & Davies, in press) to data visualisation and facilitated geo-data exchange (<http://www.usgs.gov>). Many national research agencies visualise their data using virtual globes. For example, the USGS provides streamflow, watershed, or earthquake data for display in Google Earth. The National Snow and Ice Data Centre (NSIDC) offers information about ICESat data, NASA's Ice, Cloud and Land Elevation satellite (http://nsidc.org/data/virtual_globes/glas/anchorage.kml). The application localises each laser footprint acquired by the satellite and provides further information on physical parameters (e.g. waveforms of laser reflection) of the data that help researchers choose the right data set for their purpose (Ballagh et al., 2010). Land cover and landform changes are ideal information for display in virtual globes, as overlays can be used to depict different time slices of imagery. Terrascope, for example allows the rapid comparison of Landsat imagery at different time slices that document land cover changes in the tropics (<http://www.ambiotek.com/terrascope>). Landform and hazardous process monitoring and inventories use virtual globes to visualise their data, such as the database of glacier and permafrost disasters compiled by the Glacier and Permafrost Hazards Group (GAPHAZ, <http://www.geo.uio.no/remotesensing/gaphaz/home.html>).

Virtual globes not only enhance spatial thinking, which is regarded as an "educational necessity", but augment science in general far beyond simple data visualisation (Ballagh et al., 2010). Geomorphologists use virtual globes like Google Earth or NASA World Wind for fieldwork planning, and the localisation of study sites in presentations; however virtual globes are increasingly applied to convey scientific data and research results. Tooth (2006) states that virtual globes help to address key geomorphological questions such as scale-dependency of form, simplified by techniques like zooming. For example, tectonic and (extra-)planetary geomorphology, strongly benefit from the large scale visualisation of the global surface.

Virtual globes use data overlays covering the existing base data (e.g. satellite imagery and DEM data). Thus, visualisation via virtual globes is restricted to existing data and does not allow for more complex data analysis provided by GIS applications. The standard protocol for data overlay is the Keyhole Markup Language (KML). KML (and KMZ, the compressed version of KML) is a data format that displays geo-registered placemarks, annotations, geometries, imagery and 3D surface objects in virtual globes, comparable to HTML that displays text and imagery in the web browser. The data format is human-readable and can be written using a simple text editor (Werneke, 2008).

5 Visual Outputs

After the initial processing and analysis of spatial data, it is desirable to produce outputs of research for dissemination. This may involve graphical outputs for peer-reviewed research papers or direct public consumption. Whilst visualisation workflows remain almost entirely digital and interactive, outputs need to be targeted at the intended audience and publication medium. For spatial outputs these can be considered a “traditional” static geomorphological map that is made available in printed or digital form. These provide a permanent (up to ~100 yrs), unalterable, outcome of research and are generally intended for peer-reviewed publication.

Interactive spatial outputs are increasingly becoming common as a research outcome and as a method designed to engage stakeholders and make the outcomes of research more widely available for downstream application. Interactive maps have become a standard component on many websites and can currently be considered a state-of-the-art method for the dissemination of geomorphological data. Virtual globes provide the 3D visualisation of satellite imagery and topographic data of the Earth and are used to locate any kind of information from photographs to scientific data. A wide range of GIS applications and tools have been developed to generate internet maps either for the visualisation of research outcomes or to enhance the search for, or distribution of, scientific data. This section summarises static and interactive visualisation products used in geomorphology and introduces some examples of web mapping and WebGIS.

5.1 Geomorphological Maps

5.1.1 Legend Systems

Traditional geomorphological maps differ from other thematic maps in that qualitative information prevails over quantitative or classified data. Consequently, most geomorphological maps are compiled using descriptive symbols to represent landforms and processes. Many different symbol sets and mapping systems have evolved during the 20th century in different countries with different thematic emphases and varying usage of symbols and colour (Figure 15). Even though attempts were made to create a general legend for geomorphological maps by the International Geographical Union (IGU) in the 1960s (Demek et al., 1972), no universally applicable legend system has been established. Two main styles of geomorphological maps can be identified: (1) multi-layer maps depicting morphology, landform genesis, current processes, surface and subsurface material and chronology; and (2) simpler maps focussing on landform relationships and morphology (Evans, 2010). While the former style results in multi-coloured maps with several stacked layers of data that tend to be overloaded with information and may be hard to interpret (e.g. the German system; Barsch & Liedtke, 1980), the latter usually come in black and white and represent a reduction of information for practical purposes (e.g. the British system; Evans, 1990). In addition to more universal legend systems that provide symbols for the entire breadth of geomorphological landscapes (Barsch & Liedtke, 1980; Demek et al., 1972; Cooke and Doornkamp, 1990), specialised legends for high mountains (Kneisel et al., 1998, De Graaff et al., 1987) or hazardous processes exist (Kienholz, 1978; Kienholz & Krummenacher, 1995). An overview of selected geomorphological mapping systems is provided by Otto et al (in press).

5.1.2 Map Design

Geomorphological maps are complex thematic maps that place demands on cartographic visualisation techniques in order to provide a comprehensible and readable map. It is therefore beneficial to consider some underlying principles of cartography and map design. The basic

representations of objects on maps are the symbol primitives: point, line, and area (Robinson et al., 1995). Whether a linear feature in nature is represented by a line symbol on a map is primarily a question of scale. For example, a river could be depicted by a blue line, whilst on larger maps (with increasing size of the map items) the river would be depicted using an area symbol, covering the space between the riverbanks. The map scale also determines if a landform is depicted by a point symbol, or if it is split up into its morphological components. Rock glaciers for example could be represented by a single point symbol on small scale maps, or by the assemblage of line and area symbols that differentiate the step height of the rock glacier front, furrows and ridges and the accumulation of boulders and blocks on top of the rock glacier, if the map scale increases. Note that this is different to, and independent of, the feature types used when digitising data. For specific projects it is often the case that they may well be aligned (i.e. drumlins digitised as lines are presented on a geomorphological map as lines), however it may be necessary to use the same base data for the production of different scale maps, therefore necessity the generalisation of feature types.

A differentiation of these basic representations, to express relationships among or differences between the data, can be achieved by variations of the basic visual variables: shape, size, orientation, texture, or colour (Kraak & Ormeling, 2010; Robinson et al., 1995). For example, different classes of steps or breaks in slopes, depicting various levels of river terraces, could be visualised using different sizes or variations of the same line symbol (Figure 16). Variable symbol shapes demonstrate qualitative differences and is the most commonly applied visual variable in geomorphological maps, because of the great number of different symbols for different landforms and processes.

Colour is an important visual variable, mainly used to depict qualitative differences. However, geomorphological maps are often produced in black and white especially when they are part of a journal publication to keep production costs low. If colour is used, variation of colour characteristics, hue (colour variation), value (lightness) and chroma (saturation), are the most powerful tools to emphasise certain aspects of the map. Within cartography some colour conventions exist that should be acknowledged to avoid confusion. For example on topographic maps blue is used for objects related to water, like rivers, springs or lakes; green often represents areas covered by vegetation. A valuable assistance for colour selection is provided by the online tool "Colorbrewer" (<http://colorbrewer2.org/>). The tool assists in choosing the right composition of colours by displaying different colour schemes. Colour combinations can be tested on a complex map sample that enables the designer to experience the differentiation and perception of the colours used. In many geomorphological legend systems colours are applied to represent variations in landform genesis (Barsch & Liedtke, 1980), process domains (Gustavsson et al., 2006), or lithology (Pasuto et al., 1999).

Map layout consists of the arrangement of the map components into a functional composition and a meaningful and aesthetically pleasing design to facilitate visual communication (GITTA, 2006). Geomorphological maps often include the following elements surrounding the main map: title, legend, scale, directional indicator (north arrow), coordinate grid or border, information on coordinate system and map projection, and author credits. Often inset maps are included that show the location of the mapped area (essential for large scale maps), an overview of the geological situation, or other additional information on the study area (e.g. a slope map). These items need to be arranged carefully to guide the viewer's eyes towards the focus of the map.

Most geomorphological maps are now produced using graphics or GIS software that provide tools to facilitate map creation. However, the underlying cartographic principles outlined above remain important to produce maps that are fit-for-purpose. On a map, all information is spatially related and need to be considered holistically. The composition of map items decides if and how the reader understands the message, with perception and understanding occurring subconsciously. In order to engage map-users and enable them to develop an understanding of the meaning of the map, a visual sense of the symbols and their attributes that correspond to the intention of the cartographer is required (Robinson et al., 1995).

5.2 Digital Mapping

Digital map creation is performed either using vector graphics software (e.g. Adobe Illustrator) or GIS software. The main advantage of graphical software with respect to the generation of geomorphological maps is the great number of tools for creation and modification of graphic objects. Often these can be adjusted and customised to the user's needs and the specific requirements of the legend system applied. These functions still exceed the cartographic capabilities of GIS software.

The primary advantage of a GIS is that it enables the geographical reference system of the map to be retained, with data stored in geographical databases for later analysis. Thus, a GIS offers the ability to combine basic information on landforms such as composition and geometry with secondary data, for example from physical sampling, laboratory analyses, geophysical investigations or the results geospatial analyses within the GIS (Gustavsson et al., 2008; Minár et al., 2005). The results of GIS analyses are often compiled into maps and consequently GIS software includes mapping facilities and some graphic design capabilities. Among these are automatic tools to generate the legend, scale bar, north arrow or coordinate grid and functions managing text labels and symbols. These map elements are automatically and self-consistently updated when changes are made, for example in scale or symbol type. One challenge in the process of map production is the generation of reusable, standardised digital symbols. While many symbols for various thematic purposes exist, only a few specialised geomorphological symbols sets are available for GIS software (Otto, 2008; Otto & Dikau, 2004, Bundesamt für Wasser und Geologie, 2002; IGUL, 2010). However, due to existing cartographic restrictions of many GIS, geomorphological legends and symbols need to be simplified for application in a GIS (Gustavsson & Kolstrup, 2009; Gustavsson et al., 2006). Special symbol editors are provided to compose and define the symbol set for the map (e.g. in ArcGIS). As with graphic software, GIS software offers tools to digitise vectors (points, line, polygons) with high accuracy and the ability to modify single vector nodes.

Generating geomorphological maps using a GIS enables numerous possibilities for the dissemination of research outputs extending beyond simple paper products. Internet technologies can contribute to both the dissemination of geomorphological maps, access to geomorphologic data and help to make geomorphological knowledge available to the general public. In contrast to static digital maps (i.e. simple images of maps, for example: http://gidimap.giub.uni-bonn.de/gmk.digital/home_en.htm), dynamic web maps are characterised by interactive capabilities: the user can interact with the map by zooming, panning, querying or adding further thematic layers, with the map refreshed after each task (Mitchell, 2005). Geo-registered map data can be transferred and published in several digital ways including GeoPDF, dynamic web maps

(e.g. WebGIS), and virtual globes (e.g. Google Earth). These techniques are outlined in the following sections.

5.2.1 Open Standards

Data distribution and access in distributed web-based geospatial infrastructures need to be specified to achieve interoperability in a way that different applications (e.g. geodatabases, mapservers or clients) on various platforms (e.g. Linux, Microsoft Windows) can interact and communicate with each other. The specific needs for interoperable geospatial technologies are implemented in specifications or standards describing the basic data models to represent different geographical features. They contribute to both: i) interoperability for users “mashing” up different applications and ii) software and technology developers making complex spatial information and services universally accessible. The standards are specified by the Open Geospatial Consortium (OGC), a non-profit international standards organisation with members from commercial, governmental and research organisations (<http://www.opengeospatial.org>). It leads the development of standards to establish interoperability and ensures platform and software independent usability of geospatial services and data sharing. The standards or specifications are the main outcomes of the OGC and appear as technical documents that detail interfaces or encodings. The documents are available online, enabling software developers to build support for the interfaces or encodings into their products and services. There are currently more than 30 standards defined, the most prominent of which are web services, also known as OpenGIS Web Services (OWS), specifically: i) *Web Map Service* (WMS) - providing map images, ii) *Web Feature Service* (WFS) - to retrieve feature descriptions and, iii) *Web Coverage Service* (WCS) - preparing coverage objects from a requested region. For data description and storage XML-based languages such as GML (*Geography Markup Language*), GeoSciML (*GeoScience Markup Language*) or KML (*Keyhole Markup Language*) have been developed. XML is an acronym for *Extensible Markup Language* which is a set of rules for document encoding, comparable to HTML (*Hypertext Markup language*). The OGC specifications and standards have greatly influenced the direction of web-based GIS developments making it much easier to publish, visualise and exchange any geospatial data over the internet (Mooney & Winstanley, 2009). Basic functionality, advantages and limitations of WMS and KML are discussed below and exemplified by case studies. In addition to specifications and standards, the OGC publishes several White and Discussion Papers or Best Practice Guides (e.g. GeoPDF Encoding Best Practice Version 2.2; Graves and Carl, 2009). The next section introduces the GeoPDF, a merging of geospatial data with the PDF file format.

5.2.2 GeoPDF

A GeoPDF, an OGC standard, includes one or multiple map frames within a Portable Document Format (PDF) page associated with a coordinate reference system (Graves & Carl, 2009). It enables the sharing of geospatially referenced maps and data in PDF documents. Multiple, independent map frames with individual spatial reference systems are possible within a GeoPDF for example for map overlays or insets. Geospatial functionality includes scalable map display, layer visibility control, access to attribute data, coordinate queries, and spatial measurements. Adobe Reader (starting with Version 9.0) supports the geospatial functions of GeoPDFs, however full GeoPDF functionality requires the free TerraGo plug-in for Adobe Reader (<http://www.terrago.com>). GeoPDFs can be created either directly from a GIS (e.g. ArcGIS 9.3) or using bespoke software (e.g. TerraGo Publisher or Map2PDF). A GeoPDF enables fundamental GIS functionality outside specialised GIS documents, turning the formerly static PDF maps into

interactive, portable, geo-referenced maps. It is an interesting and valuable way of dissemination for geomorphological maps. Some geospatial data providers, such as the United States Geological Survey (USGS) or the Australian Hydrographic Service (AHS), have already started publishing interactive maps using the GeoPDF format (<http://store.usgs.gov>).

5.2.3 Principles of Web mapping and WebGIS

Web mapping is a common way of presenting dynamic maps online. It links the internet with GIS technology and enables visualisation, localisation and dissemination of geo-registered data. Web mapping applications such as Google Maps or Bing Maps, providing access to street data or aerial imagery, are very popular and widespread and have increased the interest and access to mapping. Mooney & Winstanley (2009) point out that Web mapping and WebGIS applications are key components in the distribution of geospatial data and information. In addition to accessibility, developers should address the representation of input data sets and output delivery structures which need to be suitable for both the Internet delivery medium and the intended audience.

Depending on the system components, advanced symbols, map overlays from different applications and their integration into a Desktop GIS are possible. Interoperability is achieved through the use of OGC standards that include mechanisms for the integration and visualisation of information from multiple sources. The terms *Web mapping* and *WebGIS* are often used synonymously although they do not necessarily refer to the same technologies. When analytical GIS functionality is provided, the term WebGIS is generally used (Mitchell, 2005; Mooney & Winstanley, 2009). GIS processing is performed online using a GIS server and maps are visualised in interactive web viewers (e.g. OpenLayers - www.openlayers.org, MapBender - www.mapbender.org, ka-Map! - www.ka-map.maptools.org, MapBuilder - www.mapbuilder.net, Google Maps - maps.google.com, or Bing Maps - www.bing.com/maps). Although there are many ways to develop a WebGIS or to access web maps, depending on the software components used, most applications are based on the same principles (Figure 17).

The principles are as follows. The user operates a web mapping client in an internet browser that provides selected GIS functions (e.g. zooming or panning, data query, layer selection). The software compiles the user requests and forwards them to the application server (Figure 17a). The server passes the map requests to the mapserver, the central software performing the GIS processing. The mapserver, having access to the spatial data, executes the map requests and returns the maps as images to the web server, which finally serves them back to the user's web mapping client. The application acts as a web-based information system. One popular package is Maptool's "MapServer for Windows" (<http://www.maptools.org/ms4w/>), which uses open source components to provide a mapserver environment including libraries for data input and output. MapServer is GIS software running on a webserver that enables interaction with GIS data over the internet and generates cartographic output of geographic content. An introduction to the most common WebGIS tools is given by Mitchell (2005).

Most mapservers provide standardised web services like WMS (see above) for accessing maps online. The WMS contains the map request and parameters specifying GIS processing for the mapserver, for example: choice of layers or spatial extent. Desktop GIS (e.g. ArcGIS, MapInfo, Global Mapper) as well as internet map viewers (see above) compile WMS data providing direct access to map data from internet servers. WMS technology permits users to visualise entire GIS projects, such as a geomorphological map on the internet. Thematic layers of the map can be

provided as well as full analysis functionality, depending on the server side GIS software (e.g. Mapserver, GeoServer). Figure 18 shows a WebGIS that visualises the results of a geomorphological field mapping campaign in the Turtmann valley, Switzerland (<http://www.geomorphology.at>). The application employs MapServer generating the maps as WMS, the spatial database management system PostgreSQL (<http://www.postgresql.org>) maintaining the geometries and the web mapping client Mapbender (<http://www.mapbender.org>). Aerial images and a shaded relief map are provided as base layers and several thematic layers present information on process domains, surface materials, landforms and single processes. Due to MapServer's powerful cartographic engine, complex geomorphological symbols can be implemented and displayed. Symbols based on the legend for high mountain geomorphological systems established by Kneisel et al. (1998) have been implemented. The WebGIS map thus uses the same symbols as the printed map of the same area (Otto & Dikau, 2004). MapServer uses one symbol file that defines the composition of symbols for all types of vector geometries. Point information, such as individual landforms, is displayed using a geomorphological true type font (Otto & Dikau, 2004) and the spatial orientation of each character is achieved by providing the rotation angle as attribute data. Line features, for example crests and ridges, are constructed using multi-level symbols and advanced polygon symbols are supported by hatching or image fills. The Turtmantal WebGIS offers simple functionality of a desktop GIS such as spatial navigation, coordinate queries, length and area calculations as well as selection of single layers of information. The composed image of the map frame can be exported as a high resolution PDF (300 dpi) in A4 and A3 landscape or portrait orientation. For educational purposes, a glossary defines geomorphological terms.

Usually no restrictions exist concerning the number of WMS services included within a WebGIS application. Thus, WebGIS applications are powerful tools to disseminate geospatial information to users from different organisations (e.g. local authorities, environmental agencies). For example, the Integrated CEOS European Data Server (ICEDS), provided by University College London, visualises global and regional data provided by the Committee of Earth Observation Satellites (CEOS), a partnership of national space agencies. This WebGIS application contains more than 20 different thematic layers, ranging from satellite imagery to digital elevation data or geological and natural hazard information (<http://iced.s.ge.ucl.ac.uk/>).

It is important to note that Desktop GIS software benefits from the processing power of the local computer, while web-based applications perform all operations online in real-time and factors like bandwidth capacity, net work latency, browser type and system performance need to be considered. In addition, users expect rapid applications and instantaneous responses to their spatial queries (Mooney and Winstanley, 2009).

6 Conclusions

Geovisualisation has garnered considerable interest as a term covering a wide swathe of activities ranging from exploration, through to analysis, synthesis and presentation. An intuitive, useful definition is 'the visual depiction of spatial data', and this chapter has focused upon the use of geovisualisation in geomorphology under this definition. There is overlap between some of the techniques outlined here with other chapters in this volume, in particular those on remote sensing, digital terrain modeling, geomorphometry and spatial analysis.

A significantly increased availability and awareness of progressively more accurate and high-resolution terrain data (land, sea or planetary surfaces) has driven forward work on the visualisation and analysis of landscapes. The creation of observational geospatial data, through geovisualisation and mapping may be usefully termed 'visual processing'. In geomorphology, researchers are specifically interested in extracting parameters such as location, extent, height and volume of landforms of interest. This is still predominantly performed by manual mapping through image interpretation. Automated and semi-automated techniques also deliver landform parameters, but are beyond the scope of this chapter.

For manual mapping, interpreters should be aware of issues pertaining to the identification of landforms and specifically the minimum resolvable landform size, the effect of azimuth biasing and the concept of landform signal strength. Satellite imagery rarely provides ideal datasets and care should be taken in its selection in order to account for any inherent biases, and image processing techniques should be applied in order to enhance the imagery for the best possible visualisation. DEMs record surface elevation and it is therefore possible to focus post-processing techniques on extracting information about landforms. This would ideally involve regional-residual separation (RRS) whereby landforms of interest are isolated. Either in combination or as an alternative process, the calculation of terrain parameters (such as slope, curvature or roughness) can visually enhance landforms.

Geovisualisation also extends to interacting with data, a process that is now far more common across disciplines. This can incorporate simple methods for overlay, panning and zooming of 2D data, as well as extending to 2.5D visualisation and exploration of surface data, as well as true 3D and temporal analysis. Whilst many of these analyses are research intensive and require specialist knowledge, it is simple functions such as panning and zooming that illustrate the real power of interacting with, and understanding, spatial data. This is no better demonstrated than in web mapping applications which present "stripped down" GIS interfaces for users to explore data within a managed setting. This straddles that area of "visualisation products" that also includes traditional, paper based, cartographic outputs. Whilst they might seem radically different products, the power of the "layered" GIS paradigm for the organisation and management of geospatial data lies in the end-to-end digital workflows. That is, DEMs (or satellite imagery) form the primary data inputs and, after subsequent processing, are used as the basis for geomorphological mapping. This can then be used for the generation of output that is appropriate for the intended end-user, be that a printed map or web-mapping system. Regardless of the medium employed, care should be taken during the design phase in order to produce a comprehensible and readable map. Geomorphological maps are complex thematic maps and place high demands on cartographic visualisation techniques. Whilst geospatial communication may not be directly pertinent to the analysis and understanding of science based reasoning, stakeholder engagement has become a significant part of the research process. Researchers are now required to engage the general public in the outcomes, and relevance, of their work, whilst also making the products of their work more widely available in order to maximise downstream application and use. Web mapping systems provide the flexibility to target different end-user groups and geomorphologists should take full use of the facilities available.

This chapter has outlined current geovisualisation "state-of-the-art", however it is also pertinent to consider the potential future development of the area. Perhaps the one area that could see the greatest change is that of automated landform detection; the availability of high resolution DEMs and rapidly increasing computer processing power has driven research in to a variety of

techniques. Manual mapping remains predominant due to the simplicity and accuracy, however this should be expected to change. Dynamic visualisation techniques, and particularly areas such as temporal and 3D analysis will gradually improve, along with products designed to engage end users such as augmented reality. The greatest challenge is perhaps not so much technological, but widening the application of techniques, making them available to end-users.

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Captions

Figure 1: Examples of common methods of visualisation, Bowridge, Scotland (56.002002,-3.949882): (a) geomorphological map of glacial landforms, utilising Ordnance Survey 1:25,000 base mapping with 25 foot contour lines (see Rose and Smith (2008) for further details), (b) aerial photo (Google Earth) and (c) oblique photo (J. Rose). The arrow indicates the approximate photo orientation.

Figure 2: Field sketch of a slope profile highlighting morphological features, eastern slope of Sg. Belalong, northwest Borneo (Dykes, 1995).

Figure 3: Conceptual block diagram of high mountain environments showing landforms and processes of five major zones: 1- high altitude glacial and periglacial, 2 - free rock faces and associated slopes, 3 - degraded middle slopes and ancient valley floors, 4 - active lower slopes and 5 - valley floors. (redrawn from Fookes et al. 1985)

Figure 4: Four functions of geovisualisation (modified from MacEachren et al, 2004): exploration, analysis, synthesis and presentation. The “space” that geovisualisation activities inhabit is defined by the types of task, user and interactivity.

Figure 5: Illustration of the effects of size on the detectability of drumlins. Spatial resolution of the DEM is 50 m for (a) and degraded to 150 m in (b). Note that small landforms in the north of the area would be difficult to detect from (b) alone. Reproduced from Ordnance Survey Ireland, Copyright Permit MP001904. Irish Grid coordinates in metres, relief shaded with an illumination azimuth of 45° and illumination elevation of 45°.

Figure 6: Illustration of the effects of azimuth angle on the detectability of drumlins from a relief shaded DEM. (a) Azimuth angle parallel to the dominant drumlin orientation and (b) orthogonal to the principal drumlin orientation. Arrows indicate azimuth angle. Reproduced from Ordnance Survey Ireland, Copyright Permit MP001904. Irish Grid coordinates in metres.

Figure 7: Illustration of the effects of landform signal strength through the use of Landsat TM imagery of the same location acquired on contrasting dates (~180° solar azimuth) with (a) low solar elevation (11°) and (b) high solar elevation (48°). The images overlap with the top half of Figures 4, 6, 8, 9, 10 and 11. Irish Grid coordinates in metres

Figure 8: DEM visualisation using greyscaling. Reproduced from Ordnance Survey Ireland, Copyright Permit MP001904. Irish Grid coordinates in metres.

Figure 9: Example of one simple method of regional-residual separation (RSS) applied to a profile across the DEM (Hillier & Smith, 2008). (a) 1 km x 1 km median sliding-window filter is used to approximate regional relief (hills; regional indicated by the bold line, (b) Subtraction of regional relief from the DEM to leave topographic signal (drumlins; thin line). Envelope (grey shade) is based upon filters returning maximum and minimum residual values within a 1 km x 1 km kernel, (c) Normalization of heights, equivalent to a local contrast stretch, so that landforms of differing amplitude may be effectively displayed using a single colour palette and (d) Display of relative elevations using grey scale. Irish Grid coordinates in metres. Profile is along white line.

Figure 10: DEM visualisation using (a) gradient and (b) curvature. Reproduced from Ordnance Survey Ireland, Copyright Permit MP001904.

Figure 11: DEM visualisation using (a) roughness and (b) local contrast stretch. Reproduced from Ordnance Survey Ireland, Copyright Permit MP001904.

Figure 12: Red, green and blue (RGB) colour cube. The cube defines the intensity of each primary colour, so allowing the 3D plotting of each pixel colour within the cube. The grey line shows how colours are plotted for a greyscale each where each RGB component has equal intensity.

Figure 13: False colour composite generated using topographic openness (red; 51x51m kernel), topographic openness (green; 501x501 m kernel) and slope (blue) (after Anders et al, in press).

| **Figure 14:** 2.5D fly-through generated using DEM data.

Figure 15: Symbols for moraine ridge and fluvial terrace from different geomorphological legend systems (Otto et al., in press).

Figure 16: Mapping different levels of fluvial terraces using classified line symbols.

Figure 17: Simplified scheme of information and data transfer of a WebGIS and Web Service application.

Figure 18: The graphical user interface (GUI) of the geomorphological WebGIS application Turtmantal (Universities of Salzburg and Bonn, available at <http://www.geomorphology.at>).

Glossary

ALS: Airborne Laser Scanning

Bathymetry: Depth of the Earth's surface in water covered areas e.g. seafloor depth.

Decluttering: Regional-residual separation performed on a DSM with the intention of removing superficial clutter to leave 'bare earth' heights in a DTM.

DEM: Digital Elevation Model. Synthesised height data, here specifically referred to as regularly spaced grid (x,y) data each with an associated z value. See also DTM and DSM.

Detectability: How readily a landform may be distinguished or correctly identified by an interpreter in an image that is displayed. May be extended to automated software distinguishing landforms in raw, pre-display gridded data.

DSM: Digital Surface Model. A DEM representing the highest, upper surface of all visible objects within a landscape (e.g. vegetation) as recorded using a particular measurement technique.

DTM: Digital Terrain Model. A DEM of the Earth's surface free from anthropogenic features (e.g. buildings) and vegetation (e.g. trees).

Elevation: Height above a reference datum, historically sea level.

Geomorphology (vb): To work to understand the form and processes that shape the Earth or other planetary surfaces, and how they have evolved through time.

Geovisualisation: Generically, the depiction of spatial data. In geomorphology, it facilitates geospatial analysis and processing. The International Cartographic Association (ICA) Commission on Geovisualisation (<http://geoanalytics.net/ica/>).

Heuristics: Using experience-based rules to solve a problem.

Hyper-spectral Imagery: Imagery produced from an instrument with sensors sufficient to create observations across a continuous spectrum at each pixel. Contrasts to multi-spectral measurement of narrow, discrete and separated frequency bands.

Kernel: In image processing, the width of a spatial filter.

Landform: A shape or morphology within a landscape identified as a distinct entity.

Multi-spectral Imagery: Imagery created from an instrument with sensors sensitive to a different 'band' or relatively narrow range of wavelengths in the electromagnetic spectrum. **Panchromatic**

(image): an image created using wavelengths across the visible spectrum recorded in a single band and thus rendered in grey-scale. **Point Cloud:** Data format consisting of irregular (x,y,z) triplets.

Raster: DEM data format where elevations (z) are presented in a regularised spatial (x,y) grid. For satellite imagery and DEMs, reflectance at the sensor and surface elevation, respectively, are stored.

Raw Data: Data as measured (e.g. a DEM or satellite raster), although significant processing has usually been applied before presentation to the user community.

Regional-Residual (Relief) Separation (RRS): Numerical operation to isolate a layer of spatially varying vertical thickness related to features of interest from a DEM.

Sounding: Measurement of depth. See bathymetry.

TLS: Terrestrial Laser Scanning.

Topographic Signal: the presence of landforms of interest in a particular study as expressed in datasets such as height.

Signal-to-noise ratio: Ratio of information about the landforms of interest (i.e. topographic signal) to all other features in the image or DEM. May be increased by filtering the data before viewing, or by how the data are displayed.

Topography: Specifically, the shape of the Earth's surface (e.g. land elevation) although more broadly it may not just include relief but also vegetation and man-made features.

Visual Processing: The act of interrogating a terrain or landscape for the purpose of landform identification or in order to generate other derived observational data sets.

VNIR: visible and near infra-red light. These wavelengths of the electromagnetic spectrum are commonly imaged by satellites and therefore grouped together.

Cross-References

Vol. 3 Remote Sensing and GIScience in Geomorphology

3.9 Digital Terrain Modeling (Wasklewicz)

3.10 Geomorphometry (Wilson)

3.11 Remote Sensing and GIScience in Geomorphological and Landform Mapping (Bishop)

3.14 Spatial Analysis and Geocomputation in Geomorphology (Abrahart)

Biography

Mike J. Smith

Mike J. Smith was born in 1971. He received a B.Sc. (Hons.) degree in geography from the University of Wales, Aberystwyth, an M.Sc. degree in geography from the University of British Columbia and a Ph.D degree in palaeo-glaciology from the University of Sheffield.

He is currently a Senior Lecturer in GIS in the School of Geography, Geology and the Environment at Kingston University, principally lecturing to bachelor and masters programmes on the application of remote sensing in the geosciences. His research interests are based around the application of digital elevation models in geomorphology and specifically focused upon the visualisation and geomorphometric modelling of glacial landscapes. Recent interests also include field spectroscopy of loess. He is the founder and Editor of the Journal of Maps.

John K. Hillier

John K. Hillier was born in 1977. He received B.A. (M.A. Cantab) and M.Sci. degrees in Natural Sciences specialising in Geology from the University of Cambridge, and a D.Phil degree in Marine Geophysics from the University of Oxford.

After studying he was awarded a research fellowship at St Catharine's College Cambridge, and then worked for Zurich Insurance as a catastrophe modeller. He is currently a Lecturer at Loughborough University, with research interests in geohazards and quantitative geomorphology to understand Earth surface and solid Earth processes. Recent interests include drumlin formation, volcano formation, evolution of oceanic tectonic plates and the correlation between natural perils.

Jan-Christoph Otto

Jan-Christoph Otto was born in 1974. He studied Geography, Geology and Soil Science at the Universities of Bonn and Grenoble. He received his Diploma and PhD in Geography from the University of Bonn.

He is currently a Post Doctoral researcher in the Department of Geography and Geology, University of Salzburg within the Geomorphology and Environmental Systems Research Group. His main research interests include landscape change in high mountain environments with special focus on sediment budgets and the dynamics and consequences of permafrost changes in mountain areas. His recent interests include the creation of digital geomorphological maps and the combination of high resolution surface and subsurface data within a Geomorphological Information System.

Martin Geilhausen

Martin Geilhausen was born in 1979. He studied Geography at the University of Bonn and received a Diploma investigating fluvial and glacial deposits using geophysics.

After working for a geoinformation company, where he developed webGIS and web mapping applications, he enrolled as a PhD student in the Department of Geography and Geology, University of Salzburg (Geomorphology and Environmental Systems Research Group). His research involves the quantification of recent and postglacial sediment dynamics in glacier forefields, Austrian Alps. Martin is applying a suite of field techniques ranging from fluvial erosion measurement and geophysics (ground penetrating radar, seismic refraction and resistive tomography) to terrestrial laser scanning.